NEW

Exploration | Solar System | Deep Space | Space Science | Future Tech

# All About Space Annual

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Challenging Einstein's laws

Seeking out new exoplanets

Black hole secrets revealed

Solving the gamma-ray mystery

Does Planet Nine exist?

What's inside the planets?

Wonders of the universe

Exploring the surface of Mars

What is phantom energy?

Digital Edition

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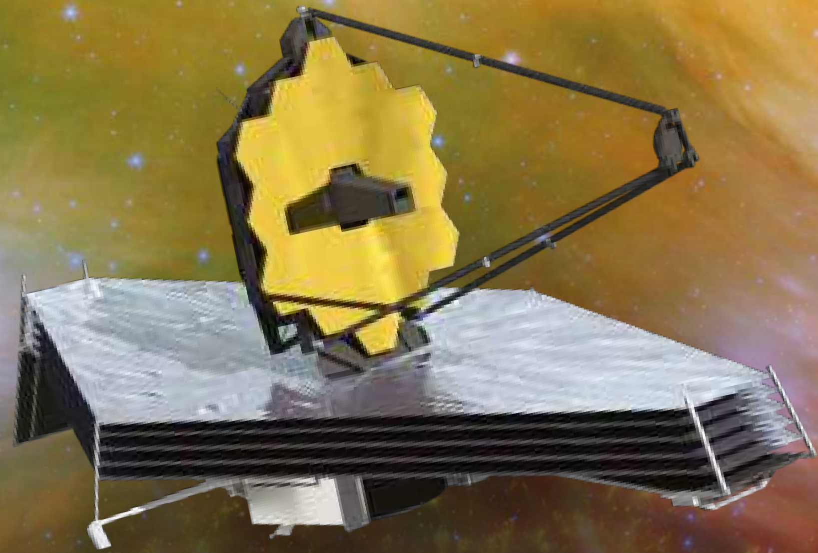
VOLUME 9

Everything you want to know about our galaxy and beyond



# Welcome to the All About Space Annual

Earth had a tough year in 2021, and while circumstances may have temporarily slowed the rate of new research and innovation in exploring outside of our atmosphere, space scientists have still very much been continuing to search for the answers to the mysteries of the universe. From the probes and rovers exploring the planets and moons of our Solar System to those searching the Milky Way – and beyond – for exoplanets, from super-Jupiters and failed stars to the hole in the universe, and from testing Einstein's well-worn laws to trying to understand phantom energy, this year's **All About Space Annual** is packed with fascinating questions and answers, theories and investigations, and much more from the past year in space science.

FUTURE

# All About Space Annual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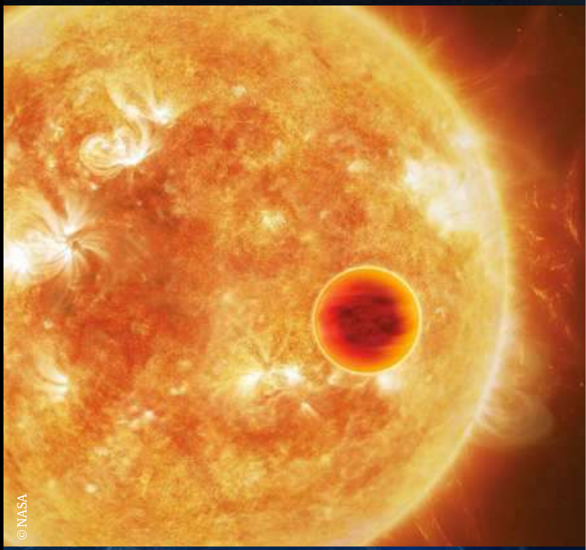
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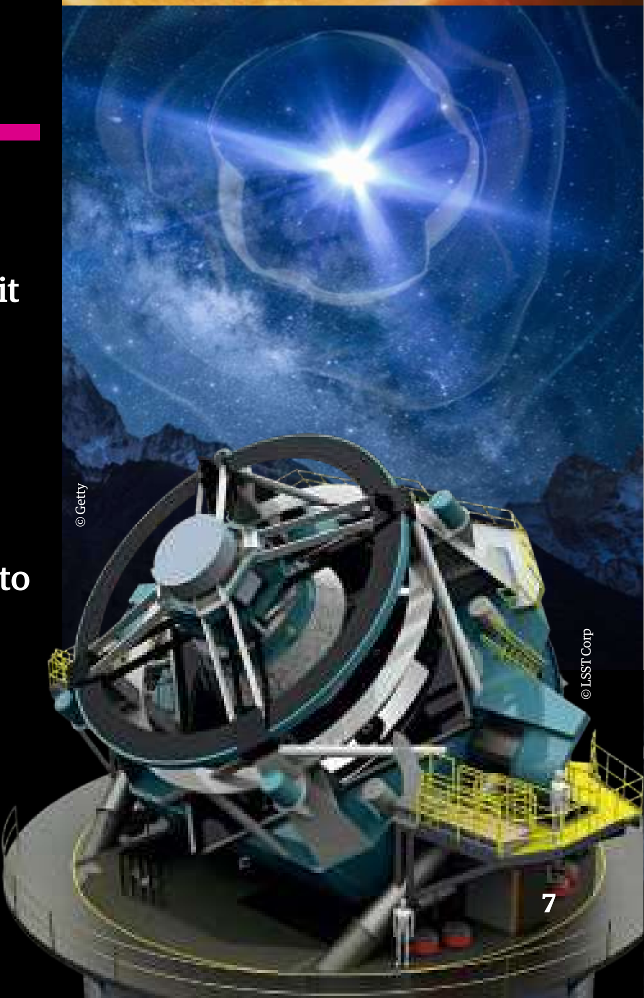
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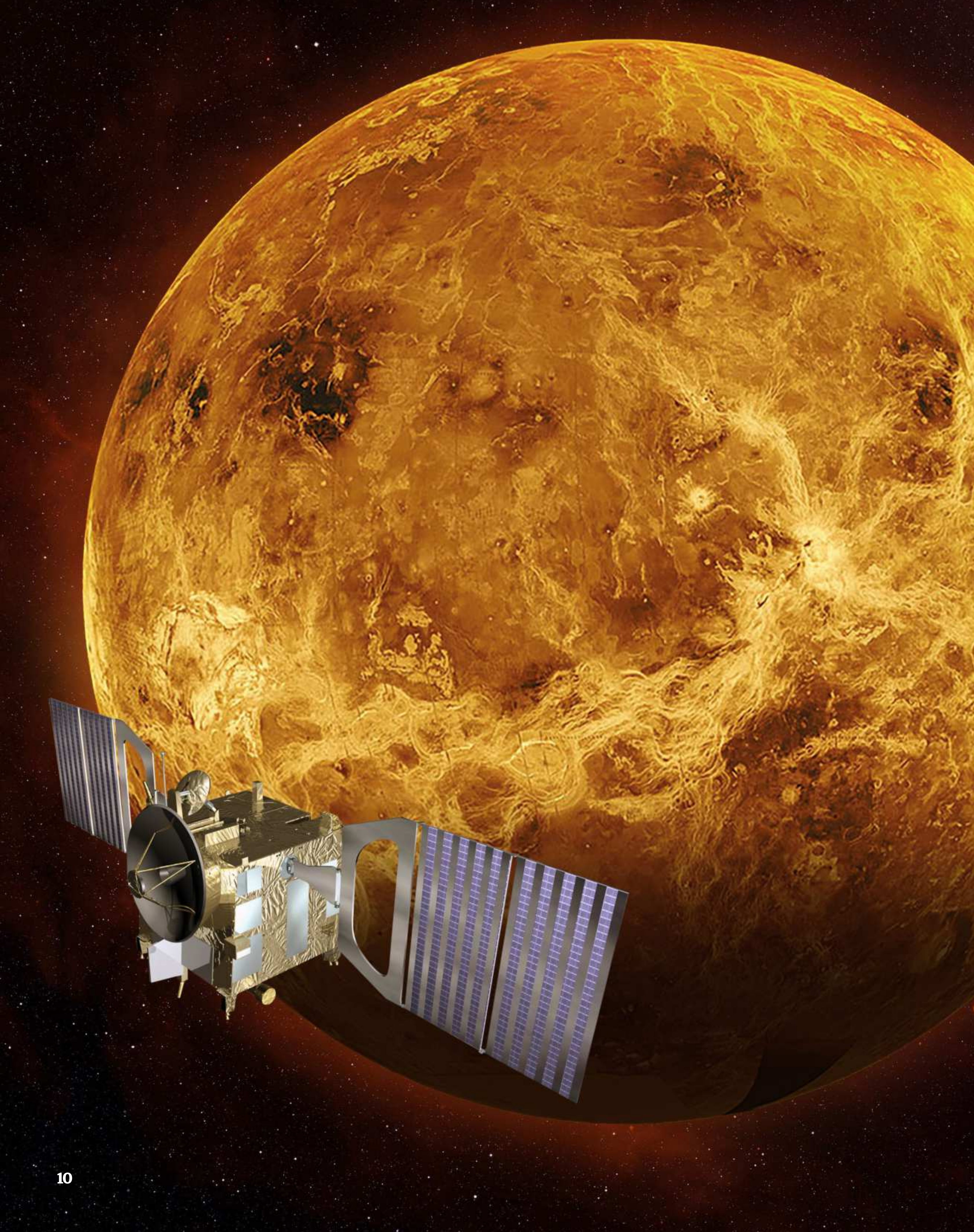
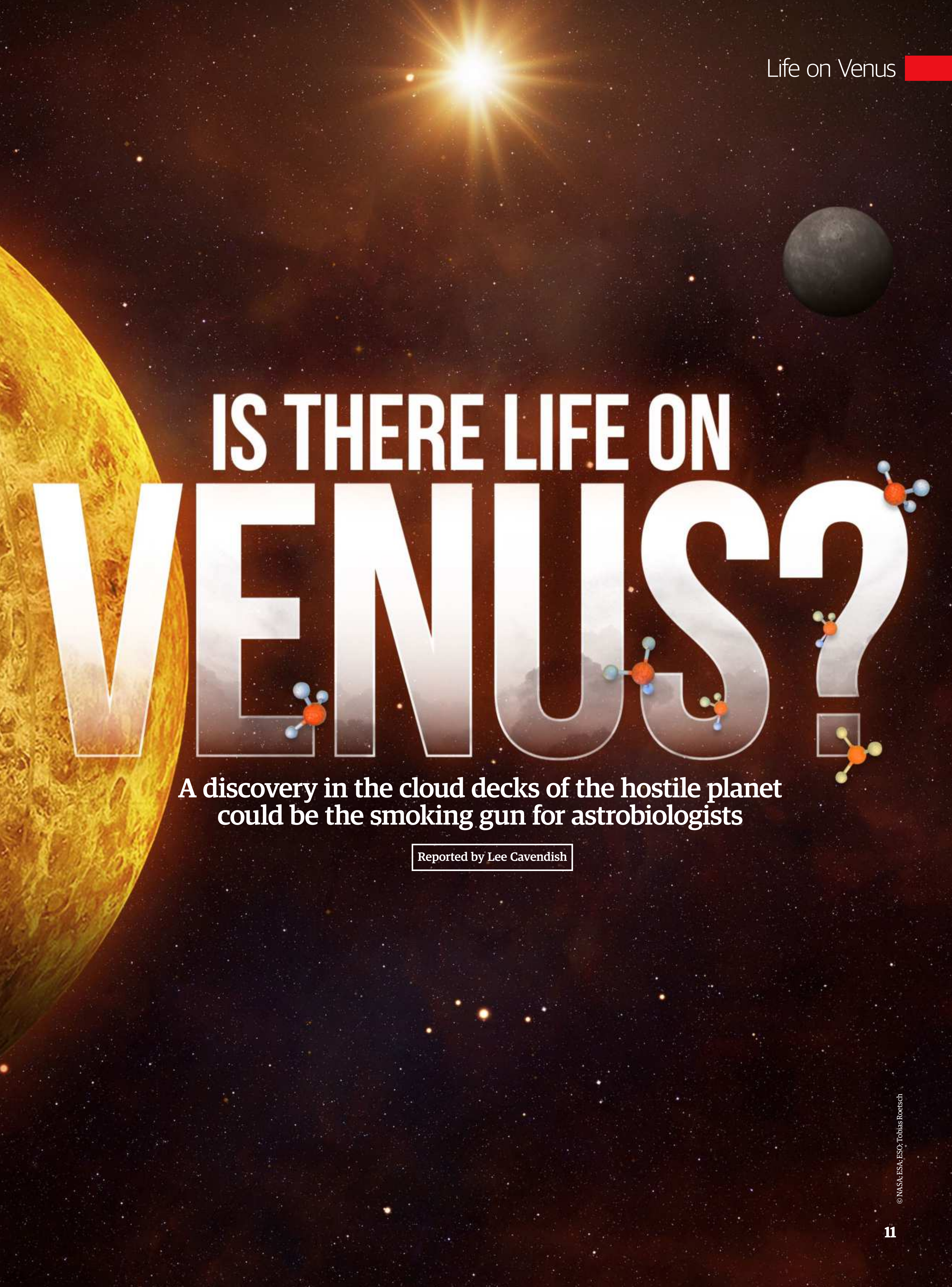
# Solar System

## Discover the secrets of our fascinating planetary system

“We have detected the phosphine on Venus. This is very exciting and was really quite unexpected”





# IS THERE LIFE ON VENUS?

**A discovery in the cloud decks of the hostile planet could be the smoking gun for astrobiologists**

Reported by Lee Cavendish

© Tobias Roetsch

# EARTH V

Sometimes called 'Earth's Twin', Venus

**AVERAGE DISTANCE FROM THE SUN**

150 MILLION KILOMETRES (93 MILLION MILES)

**PLANET RADIUS**

6,378 KILOMETRES (3,963 MILES)

**PLANET DENSITY**

5,520 KILOGRAMS PER CUBIC METRE

**SURFACE TEMPERATURE**

15 DEGREES CELSIUS (59 DEGREES FAHRENHEIT)

**ATMOSPHERIC COMPOSITION**

78% NITROGEN, 21% OXYGEN, 1% ARGON

Could life be floating around in the clouds of Venus? Does Earth's sister planet have habitable conditions above the hellscape that is its surface? Have astrobiologists just found another target in the Solar System they should be investigating? These are just some of the questions that have recently come to attention after research led by Professor Jane Greaves of Cardiff University found phosphine, a potential biosignature, in the atmosphere of Venus.

Phosphine – a molecule made up of one phosphorus atom and three hydrogen atoms – is a rare find. It can be created through chemical reactions on gas giant planets, as well as being produced industrially on Earth as a fumigant, in the semiconductor-manufacturing industry and as a by-product of the illegal production of methamphetamine. On Earth it can also be created biologically by microbes that live in oxygen-free environments. As this gas is a known by-product of biological processes, also known as a biosignature, it has fuelled intense speculation about what could be hiding on the second rock from the Sun.

Although the surface of Venus is extremely toxic and unforgiving, laced in a thick atmosphere of 96 per cent carbon dioxide and clouds consisting of sulphuric acid, there are more similarities to Earth than you may think. Venus is 80 per cent the mass of Earth and 95 per cent the radius, making them relatively alike on a planetary scale. They are both rocky planets that have a surface composition consisting of basalt rock and altered minerals.

If you could jump back in time 3 or 4 billion years, Venus would be a lot cooler and a lot wetter, potentially accommodating oceans of liquid water inside a hospitable atmosphere. However, this all changed when the planet experienced a greenhouse runaway effect that insulated the planet's atmosphere and trapped more of the Sun's heat. This has resulted in the surface that can be observed today, with temperatures of 465 degrees Celsius (869 degrees Fahrenheit) and pressures similar to if you were diving roughly 910 metres (3,000 feet) under the sea on Earth.

"It's thought that much earlier in Venus' history, the surface was much cooler and wetter, and life could have possibly originated. But conditions turned very hostile," says Greaves. "But there is a long-standing theory that the smallest forms of life – these microorganisms – might have been able to evolve upwards into the high clouds."

> "MUCH EARLIER IN VENUS' HISTORY, THE SURFACE WAS MUCH COOLER AND WETTER, AND LIFE COULD HAVE POSSIBLY ORIGINATED" JANE GREAVES

# S VENUS

is in fact a very different world to ours

**AVERAGE DISTANCE FROM THE SUN**
108 MILLION KILOMETRES (67 MILLION MILES)

**PLANET RADIUS**
6,052 KILOMETRES (3,760 MILES)

**PLANET DENSITY**
5,250 KILOGRAMS PER CUBIC METRE

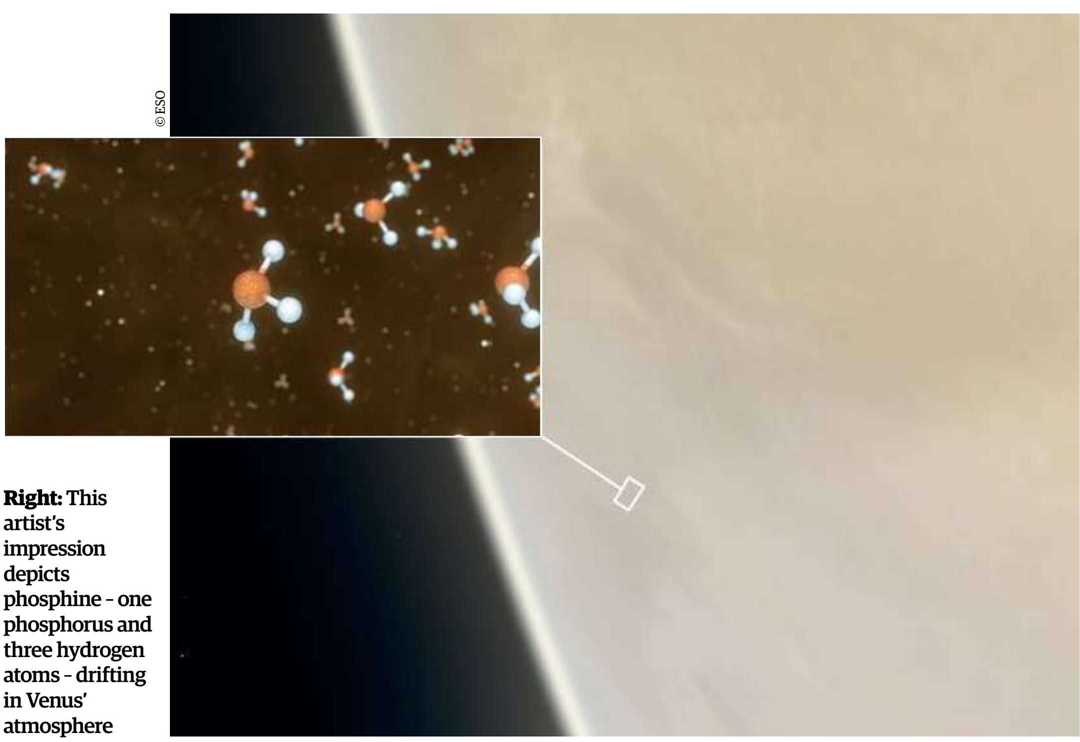
**SURFACE TEMPERATURE**
465 DEGREES CELSIUS (869 DEGREES FAHRENHEIT)

**ATMOSPHERIC COMPOSITION**
96% CARBON DIOXIDE, 3% NITROGEN

© NASA/JPL-Caltech

This discovery by Greaves originated as "an experiment made out of pure curiosity." Now it has the world talking about Venus being a possible host for life. The first course of action in making this discovery began with Greaves utilising the power of the James Clerk Maxwell Telescope (JCMT) at Mauna Kea Observatory in Hawaii, which specialises in submillimetre-wavelength observations. The JCMT was able to capture the light of Venus and perform a spectroscopic analysis of the planet, where astronomers identify a specific molecule in its atmospheric composition based on if there is an absorption or emission of radiation at a specific wavelength. This is where the first sign of phosphine was found.

"Due to the exceptional and unexpected detection of phosphine with the JCMT, although this was good data, Professor Greaves decided to get confirmation from ALMA [the Atacama Large Millimeter/submillimeter Array] to make absolutely sure," explains Dr Anita Richards of the UK ALMA Regional Centre and the University of Manchester to **All About Space**. "Also, while as a single



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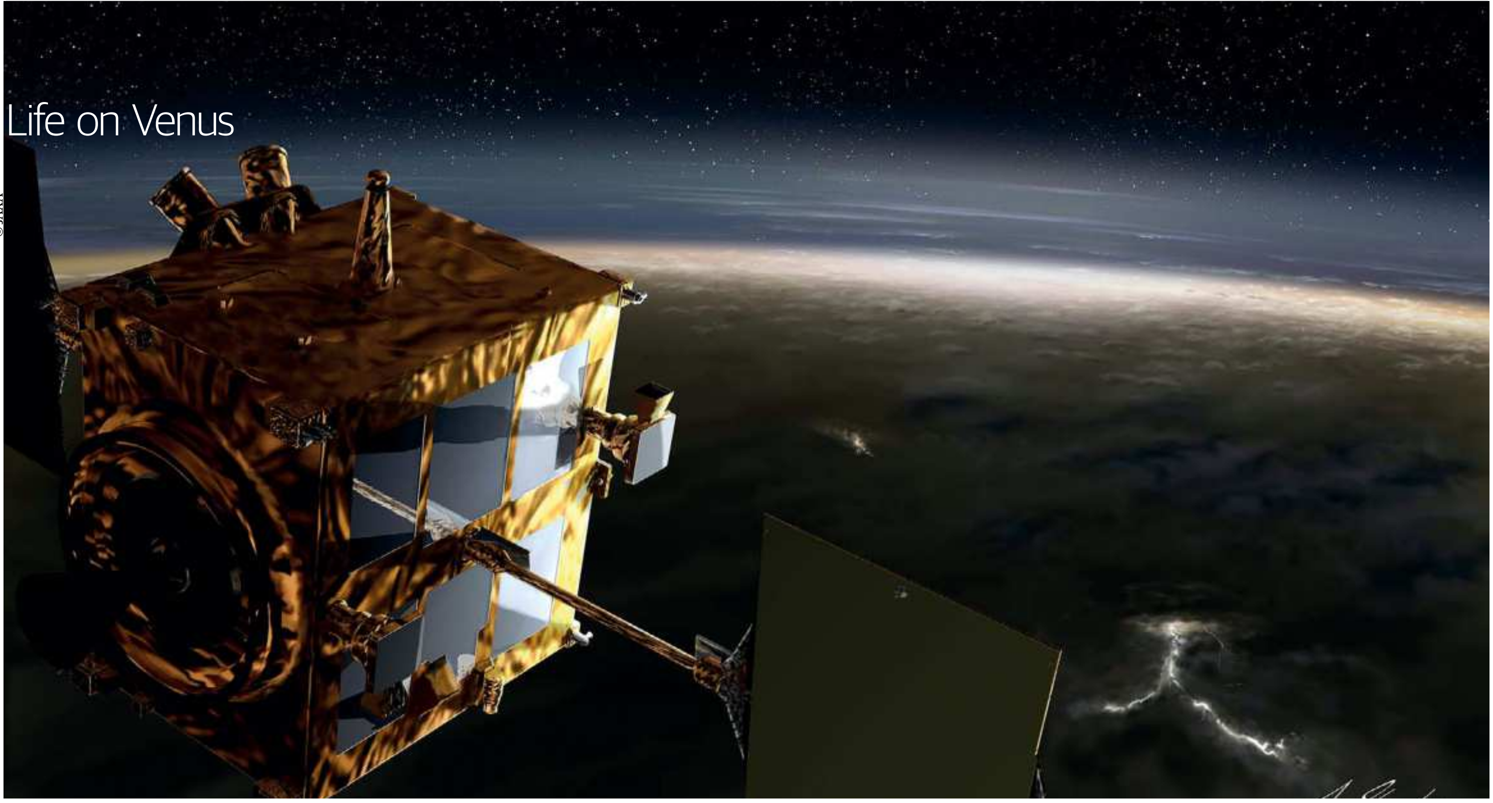
**Right:** This artist's impression depicts phosphine – one phosphorus and three hydrogen atoms – drifting in Venus' atmosphere




telescope the JCMT just sees Venus as a single blob, ALMA can see details of Venus on a similar scale as the eye can see the Moon."

This allowed the team to upgrade from the single lens of the JCMT, which has a primary mirror diameter of 15 metres (49 feet), to an array of 45 telescopes, each with a mirror diameter of 12 metres (39 feet). Since ALMA is situated in the cloudless and dry desert of Chile, it provides much more meticulous and detailed observations. Using ALMA, the same absorption dip in the spectrum was seen at the 1.123-millimetre wavelength. "Given that we did this with two completely independent observatories, what we can say with very high confidence is that we have detected phosphine on Venus. This is very exciting and was really quite unexpected," says Greaves.

Further analysis has shown that phosphine is present in an extremely low abundance: there are approximately 20 molecules for every billion other molecules. The ALMA data was also able to derive that the signal is coming from an altitude of roughly 50 to 60 kilometres (31 to 37 miles). "If you're talking about 50 to 60 kilometres up, then the pressure is much like it is at the surface of Earth, and the temperature is quite nice – maybe up to 30 degrees Celsius, or 85 degrees Fahrenheit – so it's been hypothesised that this is a living habitat today," says Greaves.

After the detection became more of a certainty, the question moved to 'how did it get there?' "We do not know. We are confident that what we know about Venus cannot make phosphine in the amounts we see, so something we do not know must be making it," says Dr William Bains of the Massachusetts Institute of Technology to **All About Space**. Before the idea of microbial life can become a viable answer, all the known chemical processes

"WE HAVE DETECTED THE PHOSPHINE ON VENUS. THIS IS VERY EXCITING AND WAS REALLY QUITE UNEXPECTED" JANE GREAVES

of Venus must be accounted for. Or, as Bains puts it: "A general rule in astrobiology is that life is an explanation of last resort. When you have ruled out everything else, then you say maybe it's life."

To start crossing possible answers off the list, the team began with investigating whether there is a photochemical process going on in the upper atmosphere of Venus that could be producing phosphine. Photochemistry is where molecules are broken down after being hit with the Sun's ultraviolet light and react with other elements to form new molecules, which is the same mechanism that creates Earth's ozone. This was not fruitful.

Next they examined if there were reactions that occur in the clouds and lower atmosphere, using thermodynamics calculations, that could account for this quantity of phosphine, but again this research did not account for the detection. Then came the question of whether there was chemistry occurring within the rocks on the surface that could be creating the phosphine and erupting it into the atmosphere. "Rock calculations using thermodynamics suggested that yes, volcanoes could produce tiny traces of phosphine, but it would be parts per quadrillion in the atmosphere, not 20 parts per billion," says Bains.

For the sake of diligence the team then looked at the possibility that the phosphine is being replenished through less obvious chemical processes. Some examples include being formed by a lightning strike, or meteorites delivering minerals that then react with Venus' atmosphere to create

**Above:** Japan's Akatsuki is the only active spacecraft currently in orbit around Venus

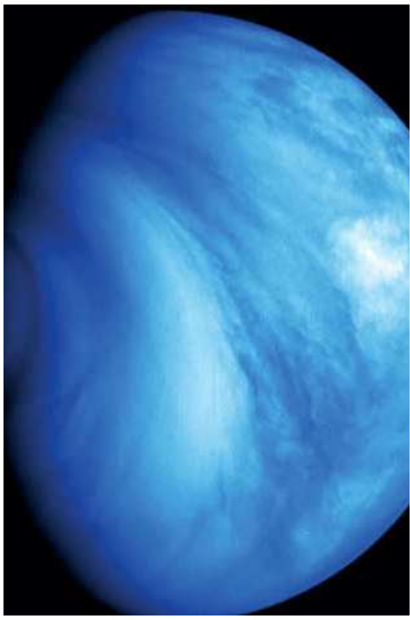
**Right:** Life has been found latched onto hydrothermal vents at the bottom of Earth's oceans – an unlikely location

phosphine. Analyses showed that the production rates for these other potential mechanisms still fall short by a factor of millions. "That really left us with two possibilities. The first is that there is some completely unknown and exotic – and therefore very exciting – chemistry going on in the clouds of Venus," says Bains. "Or, and this is the more exciting one, that the phosphine is being produced by life."

While this claim is hampered by a lack of direct evidence, there is now weight behind this argument. As Greaves has stated, there has been a long-standing theory that there are microorganisms lingering in the clouds of Venus, and it was also noted in the scientific paper, published in *Nature Astronomy*, that organisms on Earth only need to work at ten per cent of their maximum productivity to produce the observed quantity of phosphine.

Life already exists in the clouds of Earth as tiny bacteria that absorb water vapour and form cloud droplets and ice nuclei, which are vital for precipitation, so it's not a rogue idea that microbial life could be sitting in the clouds, but there is an issue with the composition of Venus' clouds. Venusian clouds are made up mostly of sulphuric acid – this is extremely acidic, and harmful for life as we know it. However, biologists have found many different types of life that thrive in the most unlikely of places, called extremophiles.

As an example, astronomers are extremely intrigued by the biology that thrives on Earth's hydrothermal vents, cracks in the seabed that leak geothermal heat and chemical substances, which some aquatic life survives on. The reason astronomers are so interested in these vents is because they show that life can be found in some of the harshest regions on Earth, so who is to say that there can't be extremophiles in the clouds of Venus that have developed an evolutionary trait where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**Right:** **Venus is viewed here in ultraviolet by the European Space Agency's Venus Express**

# HOW THE DETECTION WAS MADE

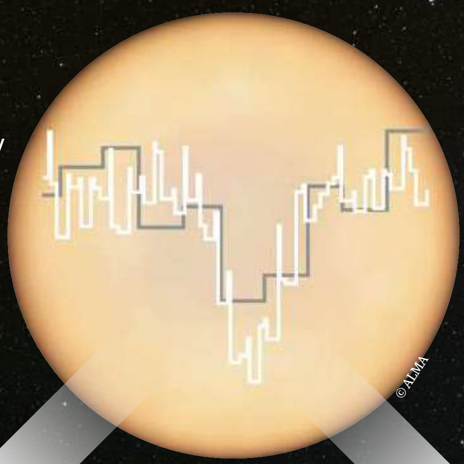
Two observatories in Hawaii and Chile were used to find phosphine's spectral signature

## 1 STARTING WITH THE JCMT

This discovery was made by performing a spectroscopic analysis of Venus' atmosphere using the JCMT in Hawaii, which is operated by the East Asian Observatory. The objective was to intentionally search for phosphine, a potential biosignature, in the planet's thick atmosphere.

## 2 THE FIRST HINT OF PHOSPHINE

After analysing the data collected by the JCMT, Greaves noticed a dip in the spectrum at 1.123 millimetres. This absorption of radiation spotted in Venus' spectrum corresponds to the potential presence of phosphine molecules. However, this analysis alone was not enough proof.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## 3 FOLLOWED UP WITH ALMA

ALMA is possibly the busiest telescope array in the world. This is because it provides unprecedented levels of precision when it comes to radio astronomy. This is why Greaves turned to the Chilean array to see if the same dip at the same wavelength could be seen.

## 4 UNDENIABLE EVIDENCE OF PHOSPHINE

The ALMA data also showed the dip caused by the phosphine molecules, and this additional data certified its existence. The ALMA data was also precise enough to provide details about the height from which the phosphine molecules are situated and its variation in latitude.


© William Montgomerie
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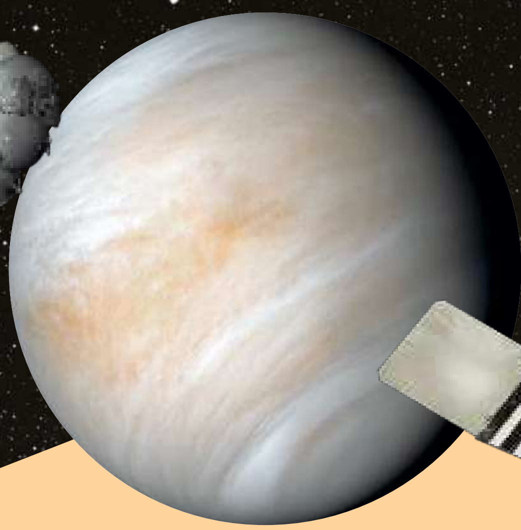
# WHAT COULD THE FUTURE HOLD FOR THE EXPLORATION OF VENUS?

With this recharged interest in Venus, here are some upcoming mission ideas that could return even more groundbreaking results



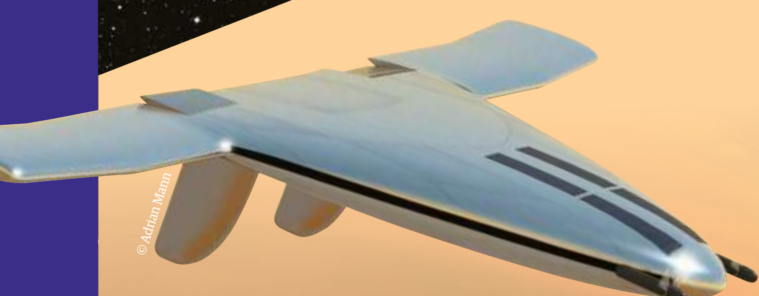
## VENERA-D

This mission concept has already been under development for around five years, and its aim is to deliver an orbiter, a lander – similar to the Soviet's Vega space probe – and one long-life surface station. This will provide data not just about the planet's atmosphere, but also the surface and interior.

## VERITAS

NASA's Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy, (VERITAS) mission is being considered as the next space exploration mission under NASA's Discovery Program. If chosen, VERITAS will map the surface of Venus and look to understand how it evolved into a world completely different from Earth.

x3 images © NASA/JPL-Caltech



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## COLONIES IN THE CLOUDS

This is certainly an idea that won't be attempted by the current crop of astronauts, but there have been conceptual ideas – bordering on science-fiction – that suggest colonies could be established in the clouds of Venus. This would provide an unrivalled opportunity to collect samples and detect direct evidence for alien microbial life.

## DRONES

Soon drones will be flying through the atmospheres of Mars (Ingenuity helicopter) and Titan (Dragonfly). Why not have drones hitching a ride on the thick and rapid clouds of Venus as well? This could be the most efficient and effective way to gain in-situ observations of the planet's upper atmosphere.

© Adrian Mann

they use the sulphuric acid as an energy source? The recent phosphine discovery has added more fuel to the fire, and this was all done using ground-based telescopes.

Exploration of Venus pales in comparison with our other neighbouring world, Mars. It has been criminally underinvestigated, even though based on the planets' semi-major axis distances Venus is closer to Earth than Mars by approximately 37 million kilometres (26 million miles). In the early 1960s, when the Soviet Union and the United States were engulfed in the Space Race, many spacecraft were launched to Venus under different programs as the two heavyweights went head to head. Punches were thrown in the form of the US' Mariner program and the Soviet's Zond and Venera programs. However, this was seemingly more out of competition than scientific discovery.

The Soviets even managed soft landings with their Venera landers, the first and most famous being Venera 7, but surface conditions were too hostile, and craft only survived for roughly 30 minutes. Technologies and rocketry have evolved immensely over the last several decades, yet the only spacecraft currently in orbit around Venus is the Japan Aerospace Exploration Agency's (JAXA) Akatsuki spacecraft. Other spacecraft are planning to fly by Venus and collect scientific data, including the Parker Solar Probe, the BepiColombo mission to Mercury and the Solar Orbiter, but observing Venus is not their primary objective.

With increased momentum now surrounding the exploration of Venus, astronomers, astrobiologists, engineers and mission decision makers are now seriously considering sending more missions there. Bains believes that there could even be a sample mission on the horizon on the back of this discovery. "I cannot imagine a sample-return mission before 2030. It would need a program, building up to a vehicle that could descend, hang around, sample and re-orbit and then return. What does it sample? Does it need to collect a few droplets or a bucket-load? From the lower haze layer or just the top of the clouds? Or both?" he asks. "A mission to fly into the clouds and analyse them – just to get an idea of what the sample mission should be sampling – is, my guess, not going to get to Venus before 2030, so 2035 at the earliest, assuming there was an Apollo-style push to do it."

However, there are some upcoming missions which could see the US and Russia return to Venus. NASA has proposed an orbiter called VERITAS that will look to understand how the planet's geodynamics have shaped its history and how this differed from Earth's. Roscosmos has proposed its own mission, called Venera-D, which will consist of two main modules, an orbiter and a lander, that will study the planet's atmospheric composition and properties up to an altitude of around 60 kilometres (37 miles), as well as other aspects about the planet's surface and internal structure.

"WHAT WE KNOW ABOUT VENUS CANNOT MAKE PHOSPHINE IN THE AMOUNTS WE SEE, SO SOMETHING WE DO NOT KNOW MUST BE MAKING IT" WILLIAM BAINS

More futuristic and innovative responses have been talked about in the recent past. Astronomers and engineers have been developing new ideas that include drones gliding through Venus' clouds. In June 2018 NASA partnered up with Black Swift Technologies, an aerospace company in Boulder, Colorado, with the intention of building a drone capable of surviving and surveying the extraterrestrial clouds. In an even more futuristic vision of exploration, there have also been discussions about whether humans could build colonies in the clouds, something reminiscent of Bespin's Cloud City in *Star Wars*.

In essence, this discovery may be looked back on in 20 years' time in the same way that astronomers nowadays look back on the discovery of Martian meteorite ALH84001. This provided tantalising results that life may exist – or have existed – on the Red Planet, and has since seen a fleet of rovers, landers and satellites sent there. Each mission has been motivated by the bacterial evidence found within ALH84001 and has continued to yield incredible results. With motivation now at an all-time high for the exploration of Venus, there are only new, exciting discoveries left to come.

**Lee Cavendish**
*Staff Writer*
Lee holds a degree in observational astronomy, which has given him the knowledge to discuss the latest complexities of the universe.

**Below:** Venusian volcanoes erupt phosphine into the atmosphere in small amounts, but not enough to account for 20 parts per billion

© NASA/JPL-Caltech

## THE ASTROBIOLOGIST'S HIT LIST

### VENUS

After this incredible phosphine discovery, the cloud layers of Venus have become another contender for astrobiological inspection.

### MARS

Mars has been a target for landers, rovers and satellites for many years as astrobiologists look to deduce if ancient life ever existed on the Red Planet.

### EUROPA

Jupiter's moon Europa appears to have a warm and salty subsurface ocean, ideal environmental parameters for supporting potential alien aquatic life.

### ENCELADUS

Similar to Europa, Saturn's moon Enceladus has a potentially hospitable subsurface ocean. However, astrobiologists know more about Enceladus thanks to NASA's Cassini mission.

### TITAN

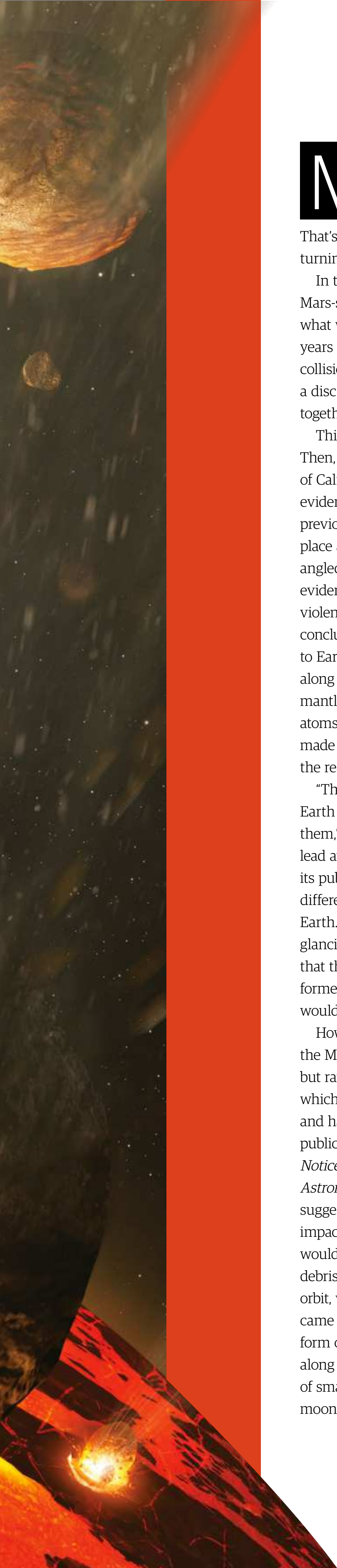
Another of Saturn's moons, Titan is a world filled with rich organic compounds, which are known building blocks for life as we know it.

A new theory suggests ‘moonfalls’ may have formed our planet’s first continents

# DID MINI-MOONS MAKE THE EARTH?

Reported by Libby Plummer

© Tobias Roetsch



Mini-moons may have battered Earth with debris in its formative years, shaping the young planet and maybe even building the first continents. That's the theory put forward by a new study, turning the 'giant-impact hypothesis' on its head.

In the well-established giant-impact theory, a Mars-sized rocky object called Theia smashed into what would become Earth around 100 million years after the Solar System was formed. The giant collision spewed debris up into space, forming a disc of debris, some of which gradually came together to form our Moon.

This idea was initially put forward in 2012. Then, four years later, researchers at the University of California, Los Angeles (UCLA) published new evidence to cement the theory. While it was previously thought that the collision, which took place around 4.5 billion years ago, was a powerful, angled side-swipe by the giant rock Theia, the new evidence confirmed it was likely to have been a violent, head-on smash. The team came to this conclusion after analysing seven rocks brought back to Earth by the Apollo 12, 15 and 17 lunar missions, along with six volcanic rocks from the Earth's mantle. A shared chemical signature in the oxygen atoms both in the Moon rocks and the Earth rocks made it likely that a head-on collision had occurred, the researchers concluded.

"Theia was thoroughly mixed into both the Earth and the Moon, and evenly dispersed between them," said Edward Young, UCLA professor and lead author of the study, speaking at the time of its publication. "This explains why we don't see a different signature of Theia in the Moon versus the Earth." The study explains that the alternative, a glancing side blow from Theia, would have meant that the vast majority of the Moon would have been formed from Theia, and thus the Earth and Moon would have different chemical 'fingerprints'.

However, a series of recent studies argue that the Moon wasn't formed by a single collision alone, but rather a series of impacts. This research, which has been published online and had been accepted for publication in the *Monthly Notices of the Royal Astronomical Society*, suggests that multiple impacts on Earth would have blown debris back into orbit, which then came together to form our Moon, along with lots of smaller mini-moons, or 'moonlets'.

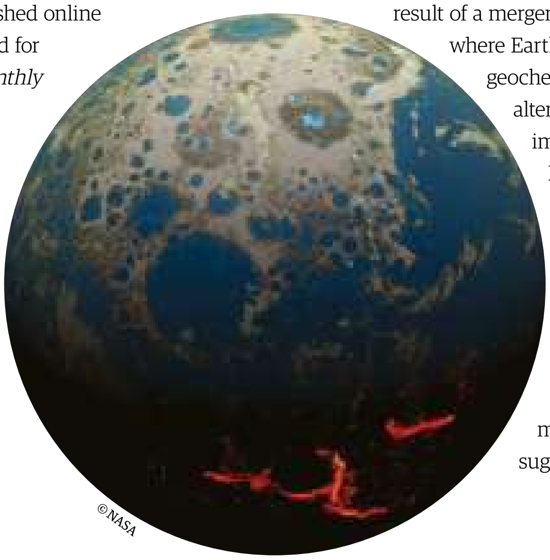
**Above:** Falling mini-moons could be responsible for the formation of Earth's earliest continents

Complex movement between these moonlets would have slowly changed their orbits, gradually making them more elliptical. Many of them would then have crashed down onto the proto-Earth, battering the fledgling planet time after time. These 'moonfalls' would have caused a build-up of material in localised spots, leading to the formation of topographical features and potentially even the Earth's first continent. The researchers were able to demonstrate the hypothesis using a series of simulations. The study was based on smoothed-particle hydrodynamical (SPH) simulations, where a computer is used to reproduce processes such as star formation and meteor impacts.

This theory was put forward as the researchers believe that the widely accepted idea of how the Moon was formed doesn't quite add up. "The current [giant-impact] paradigm is intrinsically incomplete and disconnected from the wider picture of terrestrial planet formation, in which the proto-Earth had experienced and grown though multiple planetary-scale impacts," co-author of the study Hagai Perets from the Technion Israeli Institute of Technology explains to **All About Space**. "Consideration of only the last such impact in the current paradigm disregards the critical evolution taking place prior to – and possibly following – this event."

That's why the researchers investigated the new scenario, in which Earth's Moon may be the result of a merger of lots of mini-moons, where Earth's geophysical and geochemical make-up were altered by the multiple-impact evolution of the Moon.

"The current paradigm is challenged by several major difficulties, as mentioned in this and previous papers," says Perets. "Generally, the multiple-impact model we suggest naturally connects



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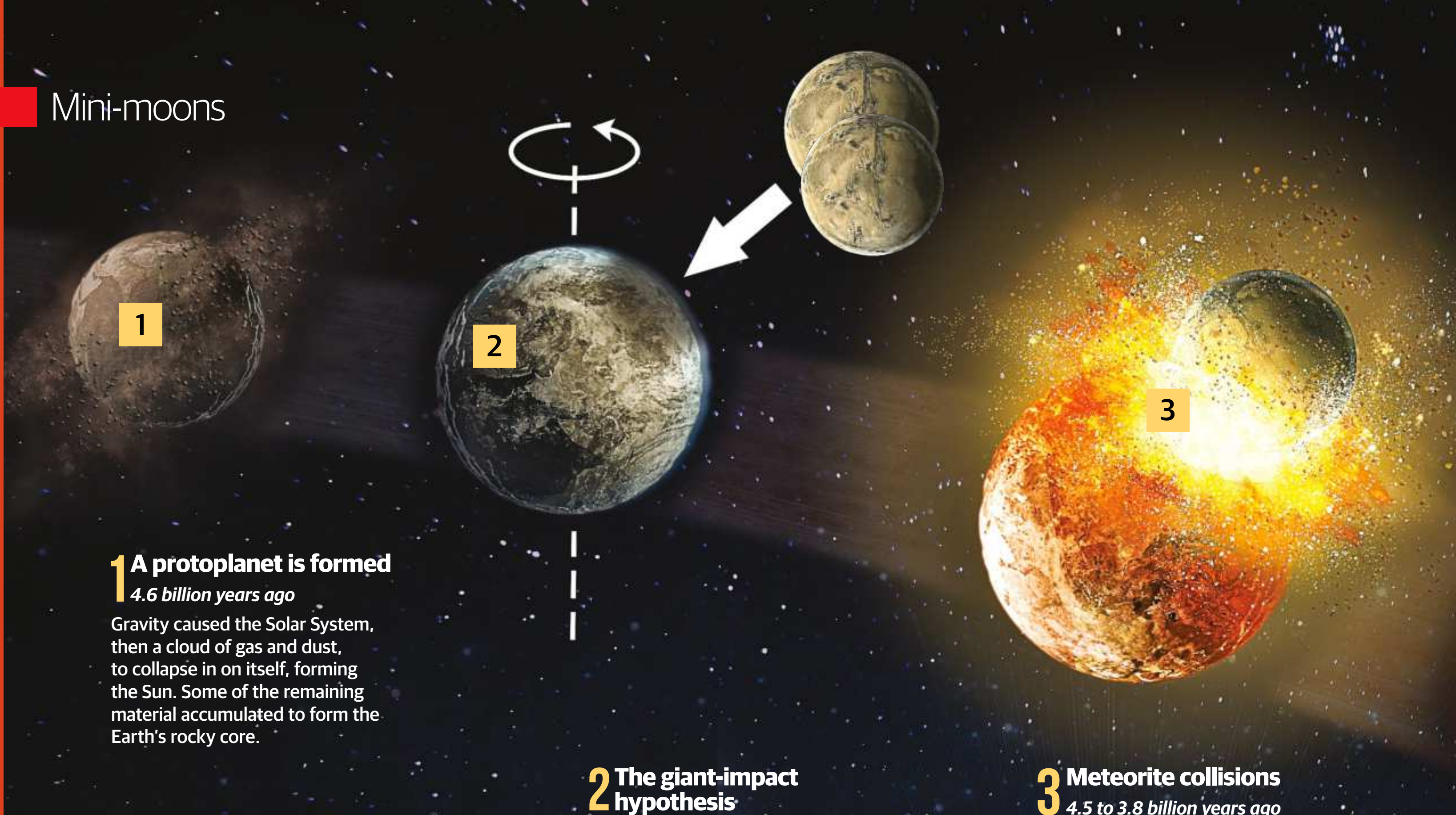
**Left:** Earth was battered by asteroids during its formation

Earth's Moon formation with the global formation of the Solar System, and potentially constrains it. These issues and challenges call for a paradigm shift and motivate the novel conceptual framework we propose. The current research on Earth-Moon collisions is one piece in this new model, and we are working on several other implications, such as studying Moon-moon collisions."

The theory builds on research published in 2017 from Perets and a different inter-university team which challenges the most prevalent theory of how the Moon formed. It suggests that the Moon we see is not Earth's first moon, but the latest in a series of rocky satellites, and that it was formed by a series of impacts rather than one big smash.

While the idea of one major collision is currently the accepted theory, the researchers behind recent studies claim that this scenario requires very specific conditions, which are rare. They claim that the idea of a series of impacts is far more feasible.

"The multiple-impact theory is a more natural way to explain the formation of the Moon," Raluca Rufu from the Weizmann Institute of Science tells **All About Space**. "It does not require one single and specific impact, but rather incorporates all the possible impactors Earth experienced during the late accretion stage [when Earth was formed]. Each moonlet accretes from a different debris disc and eventually merges with previous existing moonlets at low velocities, where the mixing between the two components is not efficient. This can explain some of the observed lunar heterogeneities in the Moon's interior," said Rufu, lead scientist of the research study published in *Nature Geoscience* in 2017.




**1 A protoplanet is formed**
*4.6 billion years ago*
Gravity caused the Solar System, then a cloud of gas and dust, to collapse in on itself, forming the Sun. Some of the remaining material accumulated to form the Earth's rocky core.

**2 The giant-impact hypothesis**
*4.5 billion years ago*
A Mars-sized rocky object known as Theia smashed into the proto-Earth, catapulting pieces of the young planet's mantle into space. Some of these pieces merged to form our Moon.

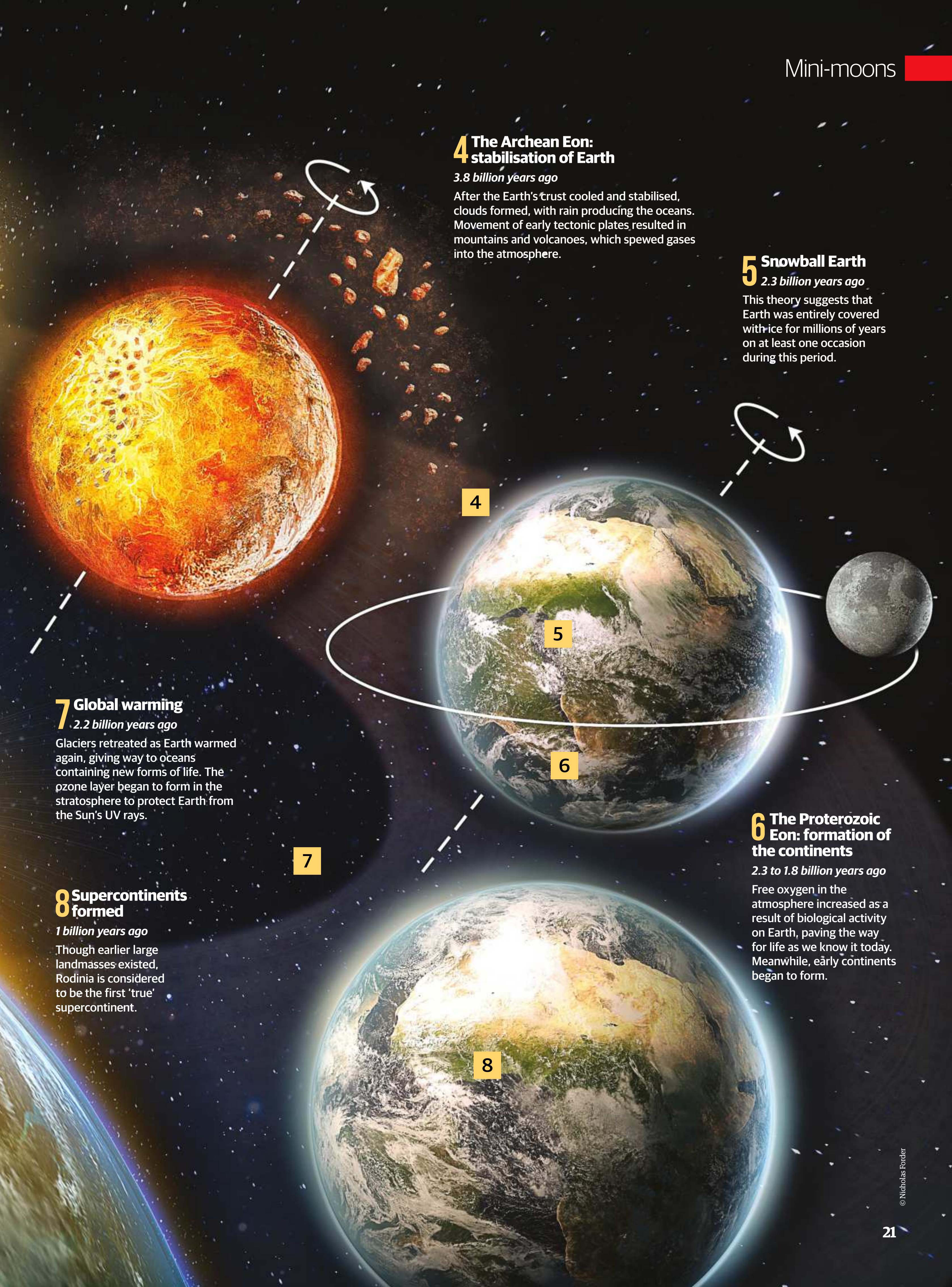
**3 Meteorite collisions**
*4.5 to 3.8 billion years ago*
Earth developed into a solid sphere after being bombarded by the remaining debris in the form of asteroids, meteors and comets, which likely deposited much of the Earth's water onto its surface.


# THE MAKING OF EARTH

The nebular hypothesis is the most widely accepted theory of how our planet formed at roughly the same time as the rest of our Solar System's worlds

**9 Pangaea formed**
*About 300 million years ago*
The supercontinent that would eventually split apart to make Laurasia and Gondwana, which then went on to become the seven continents we know today.

**10 The Tertiary Period**
*65 million years ago*
The bumping of tectonic plates led to rocks being pushed upwards to form modern mountain ranges such as the Alps and Himalayas.




## 4 The Archean Eon: stabilisation of Earth

*3.8 billion years ago*

After the Earth's crust cooled and stabilised, clouds formed, with rain producing the oceans. Movement of early tectonic plates resulted in mountains and volcanoes, which spewed gases into the atmosphere.

## 5 Snowball Earth

*2.3 billion years ago*

This theory suggests that Earth was entirely covered with ice for millions of years on at least one occasion during this period.

## 6 The Proterozoic Eon: formation of the continents

*2.3 to 1.8 billion years ago*

Free oxygen in the atmosphere increased as a result of biological activity on Earth, paving the way for life as we know it today. Meanwhile, early continents began to form.

## 7 Global warming

*2.2 billion years ago*

Glaciers retreated as Earth warmed again, giving way to oceans containing new forms of life. The ozone layer began to form in the stratosphere to protect Earth from the Sun's UV rays.

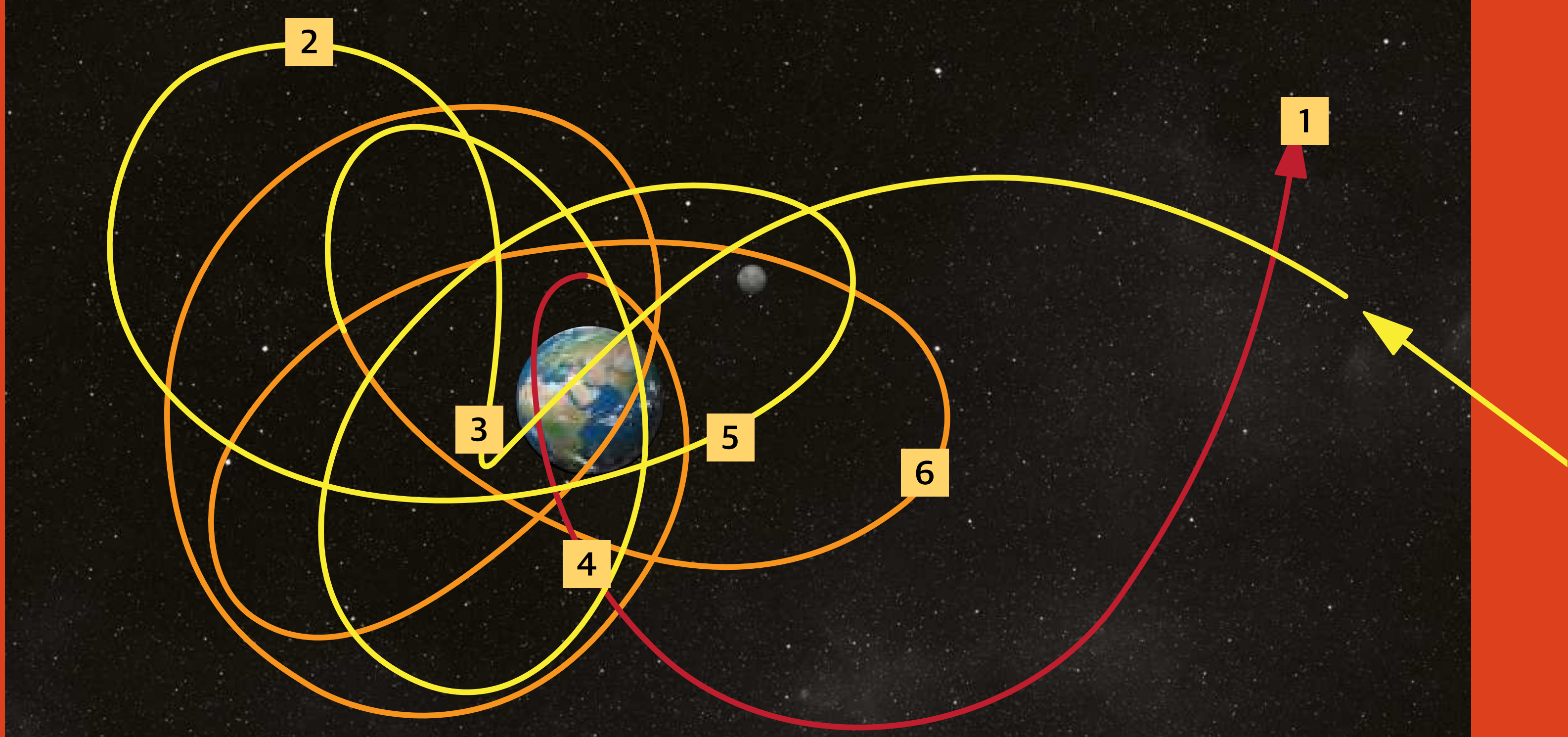
## 8 Supercontinents formed

*1 billion years ago*

Though earlier large landmasses existed, Rodinia is considered to be the first 'true' supercontinent.

# EARTH'S LITTLE MOONS

Our Solar System's planets have more than one moon – even ours on occasion




**1 Temporary visitors**
A typical mini-moon will orbit the Earth for around nine months, although some could stay in orbit for decades or more before being recaptured into orbit around the Sun.

**2 More than one moon**
The Moon isn't our only natural satellite. Asteroids orbiting the Sun can temporarily become mini-moons, following a complex path around Earth.

**3 A complex journey**
As they are tugged in different directions by the Earth, Moon and Sun, mini-moons follow complicated paths rather than neat elliptical orbits.

**4 A confirmed mini-moon**
In 2006 the car-sized mini-moon 'RH120' was discovered. It orbited Earth for less than a year before returning to the Sun's more powerful gravity.

**5 Tiny satellites**
Their small size can make them hard to spot, but experts think there could be a large amount of undetected mini-moons around the Earth.

**6 Second satellite**
In 2016 NASA's Jet Propulsion Laboratory (JPL) detected a new mini-moon, 469219 Kamo'oalewa. While actually in orbit around the Sun, it appears to circle Earth too.

The authors admit that there are limitations to the new multiple-impact hypothesis, largely that it is based on a limited dataset, making it harder to model possible collisions. "In the current model we explore the implications of moonfalls on the Earth using simulations of the impacts themselves, making use of a hydrodynamical code," explains Perets. "We consider a grid of models for the initial properties of the impact [position of the impact, size of the impacting moon, rotation of the proto-Earth] motivated by the study of dynamics leading to the infalls. This is only one piece in the overall model of the multiple-impacts theory. The main limitations are in direct predictions that can still be observed today billions of years after the fact.

"The general limitation of any Moon model [both single- and multiple-impact models] is that we have only one system to check – we don't have statistics of many moons and their properties. The other limitation is that overall the phase space of possible collisions and impacts is very large, and it is therefore difficult to model any possible type of collision. We only run a grid sampling the huge phase space of possibilities. Nevertheless, there are clear trends that suggest we can generalise our results to a wide range of collisions, so this is not a main obstacle."

If the mini-moons theory is correct and the first continents on Earth really were formed by multiple moonfalls, how exactly would we go about proving this? "The best evidence might be on the Moon," explains Perets. "For example, if we find that the composition on the far side of the Moon is significantly different than that found on the near side, it could be a clear signature of multiple moons making up the current Moon. That being said, finding a small difference – or not – would not exclude it."

Because the Moon is tidally locked to Earth we only ever see its near side, which is where all of

> "THE CURRENT PARADIGM IS INCOMPLETE AND DISCONNECTED FROM THE WIDER PICTURE OF TERRESTRIAL PLANET FORMATION" HAGAI PERETS

the Apollo lunar landings were made. We've seen the far side in photographs and satellite images, which have revealed its heavily cratered surface, but there is yet to have been a NASA mission to this uncharted territory. The China National Space Administration (CNSA), however, has landed a spacecraft on the far side of the Moon as part of the Chinese Lunar Exploration Program. Chang'e 4 touched down on 3 January 2019, achieving a milestone as the first soft landing on the Moon's mysterious far side in the Von Kármán crater. Equipped with a rover, Yutu-2, one of Chang'e 4's main objectives was to study the chemical composition of lunar rock and soil, the first to do so on the far side. A follow-up mission, Chang'e 5, landed on the near side on 1 December 2020, and will further the program's research by returning a sample of lunar rock to Earth for further study.

The idea of impacts leading to the formation of topographic features on planets' surfaces isn't new. The latter stages of planet formation are widely thought to be characterised by extremely violent, catastrophic collisions, and features such as mountains can be seen on planets throughout the Solar System. But some experts disagree that the falling mini-moons would have formed any such features on Earth.

As the Earth took around 100 million years to cool from molten magma into a solid sphere, it is questionable whether mini-moons falling during that time would have left any mark on the molten planet, as any scars left would have been covered. However, the researchers argue that the moonlets would have struck Earth after much of the planet had solidified into a crust and that the impacts would have been gentle enough to remain on the surface, rather than smashing through.

While not yet conclusive, the idea of multiple strikes on Earth producing a series of moonlets which then rained down on Earth is a compelling alternative to the accepted theory. But why is it so important? "The latter stages of accretion, named the giant-impact phase, set the final architecture of the Solar System and the composition of the final planets and their satellites," explains Rufu. "Understanding the formation of the Moon can provide insights on the environment of the early Solar System, and it may help us understand whether satellite formation in general is abundant or whether it requires unique impact conditions.

"Moreover, due to its large size, the Moon stabilises Earth's tilt and provides a somewhat stable climate for life to evolve. If detecting exomoons will be possible in the near future, then it may be more beneficial to look for life around planets with large satellites. Of course, this is somewhat speculative, as we know of only one planet that harbours life, and it happens to have a large satellite."

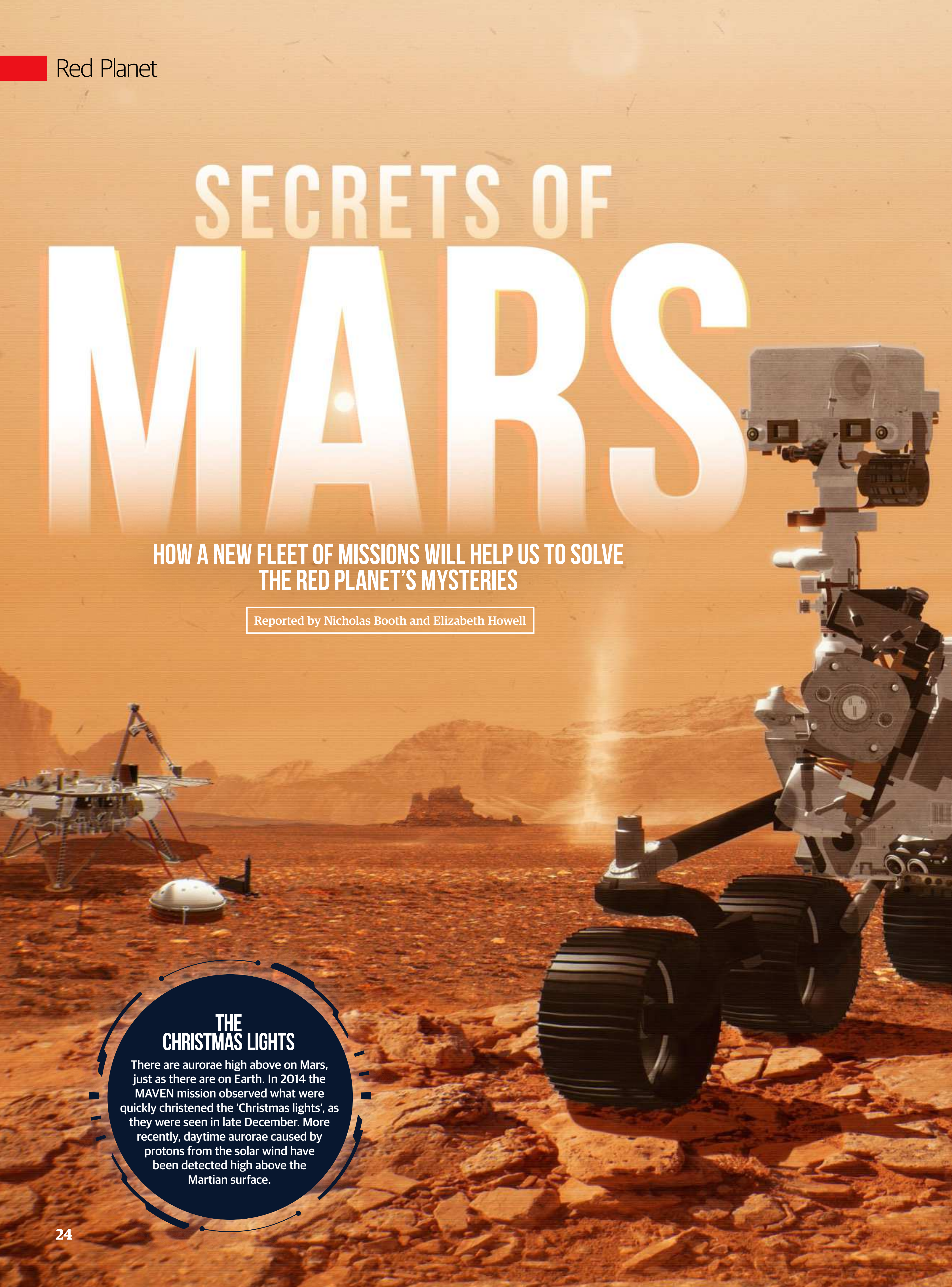
A better understanding of the impacts that shaped the evolution of Earth could give us vital insights into how life-bearing planets form. In turn, this could help us track down potentially habitable planets in future, and maybe even ensure the endurance of the human race for generations to come. If the mini-moons theory is correct, these moonlets may well have shaped not only our past, but also our distant future.

**Libby Plummer**
*Space science writer*
Libby specialises in writing about science. She has contributed to a variety of publications including *Stuff*, *Wired*, *Wearable* and *Metro*.

**Right:** UCLA researchers Paul Warren, Edward Young and Issaku Kohl with a sample of rock from the Moon

**Below:** A concept drawing of the early Earth depicts it being battered





# SECRETS OF MARS

## HOW A NEW FLEET OF MISSIONS WILL HELP US TO SOLVE THE RED PLANET'S MYSTERIES

Reported by Nicholas Booth and Elizabeth Howell

### THE CHRISTMAS LIGHTS

There are aurorae high above on Mars, just as there are on Earth. In 2014 the MAVEN mission observed what were quickly christened the 'Christmas lights', as they were seen in late December. More recently, daytime aurorae caused by protons from the solar wind have been detected high above the Martian surface.

The Red Planet keeps a tight rein on its secrets. Many enduring mysteries about Mars have taken years of research to resolve, only to be replaced by newer, ever more puzzling ones. If exploring Mars directly over the last five decades has taught us one thing, it is surely that even today – after intense scrutiny from above, on the surface and now probing directly below – the Red Planet can still spring surprises.

Mars is a freezing, desiccated desert on which a constant swirl of dust plays havoc with delicate instruments. Worse, mechanical failures and anomalies cause headaches for those who have sent robots in their stead. Even so, most researchers wouldn't have missed any of it for the world.

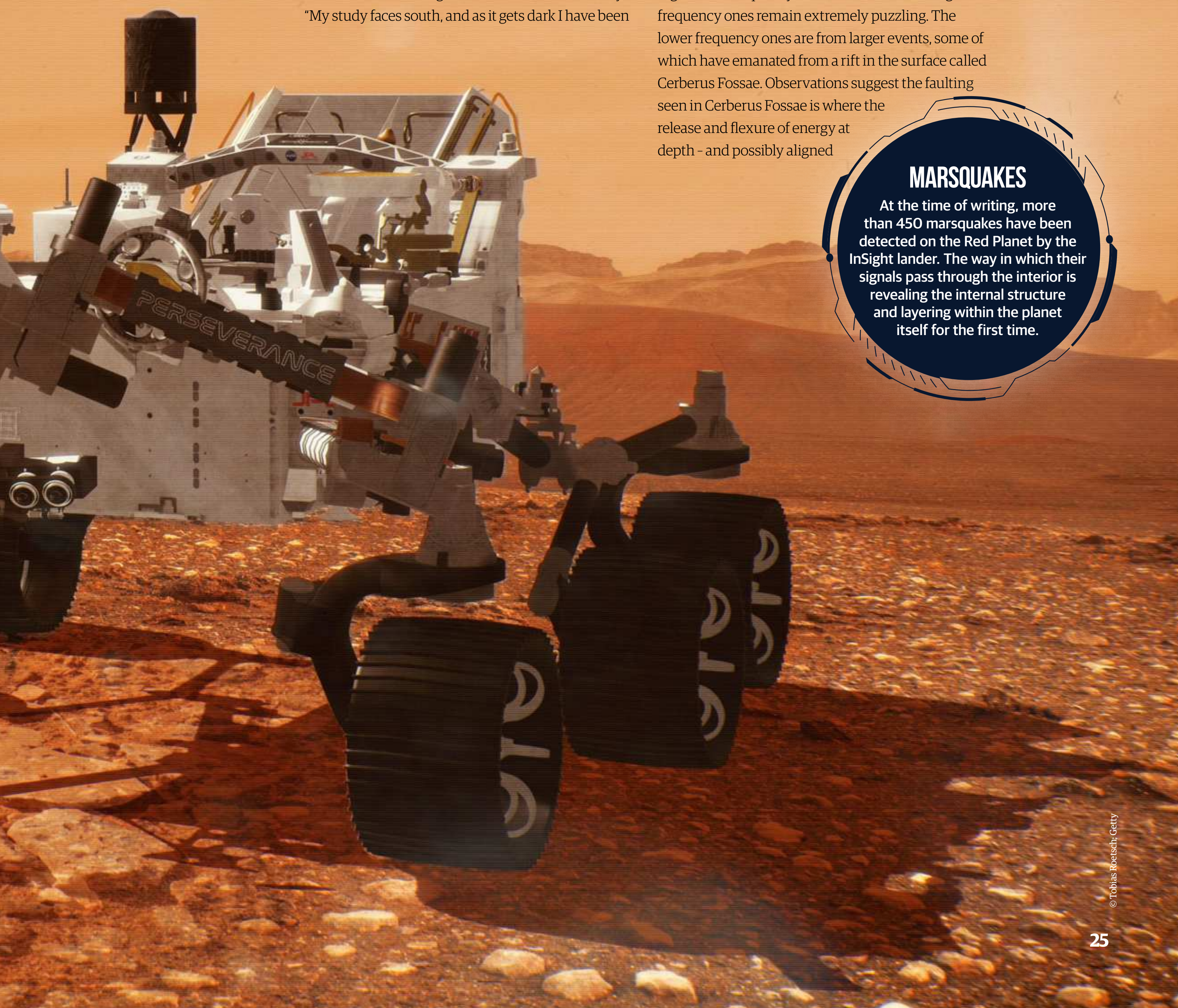
"It's been an amazing journey," says Dr Anna Horleston, a seismologist based at Bristol University. "My study faces south, and as it gets dark I have been able to see Mars rise through the window in the early evening. And then I can look down at my screen at wiggly lines, and know they have come from there."

Those lines represent one of the holy grails of Mars research, the telltale signs of seismic activity. NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) has been making detailed maps of the Martian interior for the first time. It had long been suspected that the Red Planet had a small core and was more Moon-like in terms of its activity, certainly not as seismically active as Earth. Since the InSight landing in November 2018, more than 450 marsquakes have been identified. Residual heat deep within the interior is still causing small-scale seismic waves .

"We have characterised these signals as either high or low frequency," notes Horleston. The higher frequency ones remain extremely puzzling. The lower frequency ones are from larger events, some of which have emanated from a rift in the surface called Cerberus Fossae. Observations suggest the faulting seen in Cerberus Fossae is where the release and flexure of energy at depth – and possibly aligned

## MARSQUAKES

At the time of writing, more than 450 marsquakes have been detected on the Red Planet by the InSight lander. The way in which their signals pass through the interior is revealing the internal structure and layering within the planet itself for the first time.




© Tobias Roetsch; Getty

with the faults themselves – is taking place. Some of the team believe that lava as recent as 10 million years old is the cause. The question of how much heat is still radiating outwards from a core that seems to have switched off early in Martian evolution remains one of the greater secrets yet to be revealed.

InSight is all about statistics: the more observations it makes, the greater the accuracy of its findings. For most of 2020, however, its landing site in Elysium Planitia has been windy, drowning out many of the highly sensitive measurements needed to identify marsquakes. Worse has been the cumulative effect of the fine dust which swirls around. "A lot of dust has accumulated on the solar panels," says Horleston. "We knew we would lose power over the course of the mission, but we have more dust than we'd hoped."

As greater amounts of dust have flowed into the local atmosphere, the amount of sunlight has been reduced. Worse, the spacecraft's solar panels – which provide it with power – have been covered. The mission is now literally running on half the power it had just after landing. Into 2021, that means there will be a delicate balancing act for InSight's operations team. Some instruments may have to be selectively switched off because of power limitations. The lander's robotic arm, for example, should have been put to rest in the spring of 2019. It actually spent most of its first year on Mars being used to scoop, scrape, prod, poke and push. The InSight 'mole' – a heat probe designed to drill into the surface and take measurements – would just not burrow. Even now nobody is sure what the problem was.

The Red Planet often adheres to Murphy's law. The mole would have worked everywhere else on the Red Planet where there have been landings. Now, when it has finally started to do its job, power is becoming an issue. Dust devils have also been seen at other landing sites, which whizz by and act as vacuum cleaners on solar panels. Not so with InSight. It is now essentially hibernating for the winter.

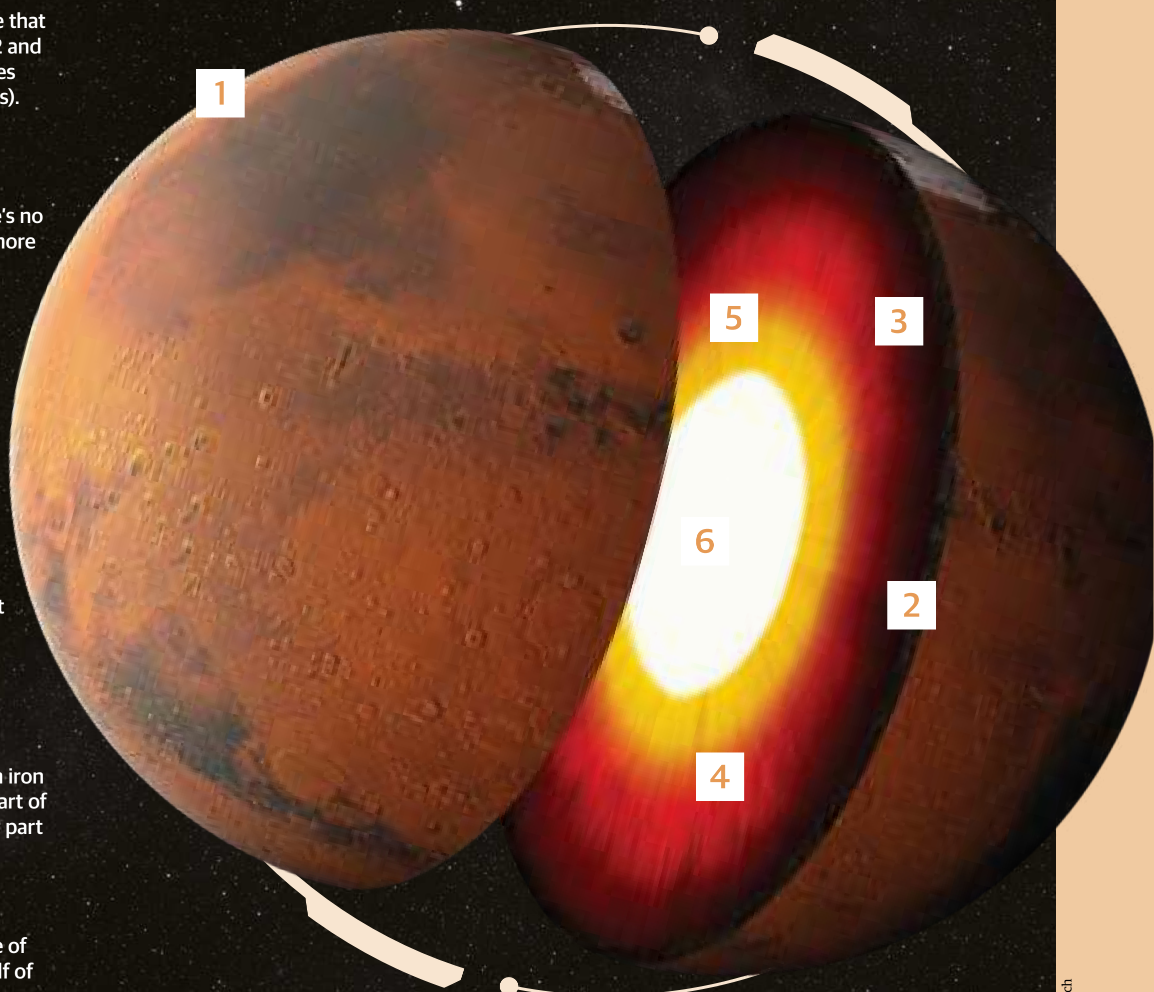
The mission will allow researchers to connect up another important part of the Martian jigsaw puzzle. The atmosphere itself is very dry, cold and tenuous, and is believed to be the remnant of a much denser atmosphere. Understanding how it degraded remains the underlying secret of the Martian climate.

### METHANE

The most elusive substance in the atmosphere of Mars today is methane, present in trifling quantities. But the European Trace Gas Orbiter has yet to find any, though recently it may have shown why. A new series of hitherto unsuspected spectral lines may be 'hiding' the underlying signals of methane.

## INSIDE THE RED PLANET

**Recent research has been unearthing some juicy secrets beneath Mars' surface**




**1 A thick crust**
Data from NASA's InSight appears to indicate that Mars' crust is between 20 and 37 kilometres (12 and 23 miles) thick on average. Earth's crust averages between 32 and 48 kilometres (20 and 30 miles).

**2 Two to three layers**
The crust is divided into either two or three layers of different types of rock, although there's no confirmation as to what they are yet. Three is more likely when analysis of Martian meteorites and geochemical models are taken into account.

**3 Marking the boundary**
Using seismology data from InSight taken in 2019, a study by researchers at Rice University concluded the boundary between the crust and mantle is about 35 kilometres (22 miles) below the position of InSight.

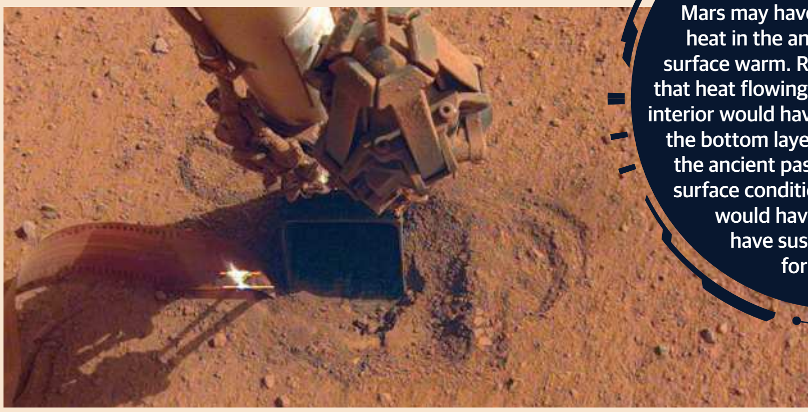
**4 A cooler mantle**
InSight found the mantle to be cooler than expected. Largely dormant mantle, it is thought to be richer in iron, potassium and phosphorus when compared to Earth.

**5 Olivine-wadsleyite transition**
The mantle also contains a zone where the mantle's mineral structure changes: magnesium iron silicates form the mineral olivine in the upper part of the zone, and wadsleyite is formed in the lower part due to high pressures and temperature.

**6 A hot core**
Mars has a metallic molten-liquid core made of iron, nickel and sulphur. It makes up roughly half of the planet's total diameter. Since it doesn't move, Mars doesn't have a magnetic field.

## GOING UNDERGROUND

Mars may have had enough internal heat in the ancient past to keep its surface warm. Researchers determined that heat flowing from within the Martian interior would have been sufficient to melt the bottom layers of thick ice sheets in the ancient past. No matter what the surface conditions were like, the heat would have been enough to have sustained life had it formed then.






**Top (clockwise): After much effort and frustration over 2020, the InSight 'mole' – its temperature sensor – has now finally burrowed beneath the surface**

**The French-British seismometer package shown under its cover, now resting on the surface of Mars**

**Layered rock on the Martian surface is shaped by wind erosion, as can be seen in this view of Arabia Terra**

## NITROUS PULSES

Observations from the MAVEN ultraviolet instrument show unexpected 'pulses' in the upper atmosphere. They are caused by high-altitude winds bringing molecules down into the lower atmosphere, which then 'pulse', accelerating chemical reactions that cause nitric oxide and the ultraviolet glow observed.

The Mars Atmosphere and Volatile Evolution (MAVEN) orbiter has been looking at how the interior of the planet relates to how the solar wind interacts with the atmosphere's outmost layers.

"MAVEN was intended to look at the upper atmosphere today as a way of understanding loss to space," says its lead scientist Professor Bruce Jakosky of the University of Colorado. "The mission's overarching goal was to determine the role that loss of atmosphere to space played in the changing climate through time."

The complex cocktail of chemistry involved shows that the outer atmosphere is selectively pulled apart by the solar wind. "The bottom line is that loss to space accounted for the single largest removal of gas from the atmosphere and was a driving factor in changing the climate some 3.7 billion years ago."

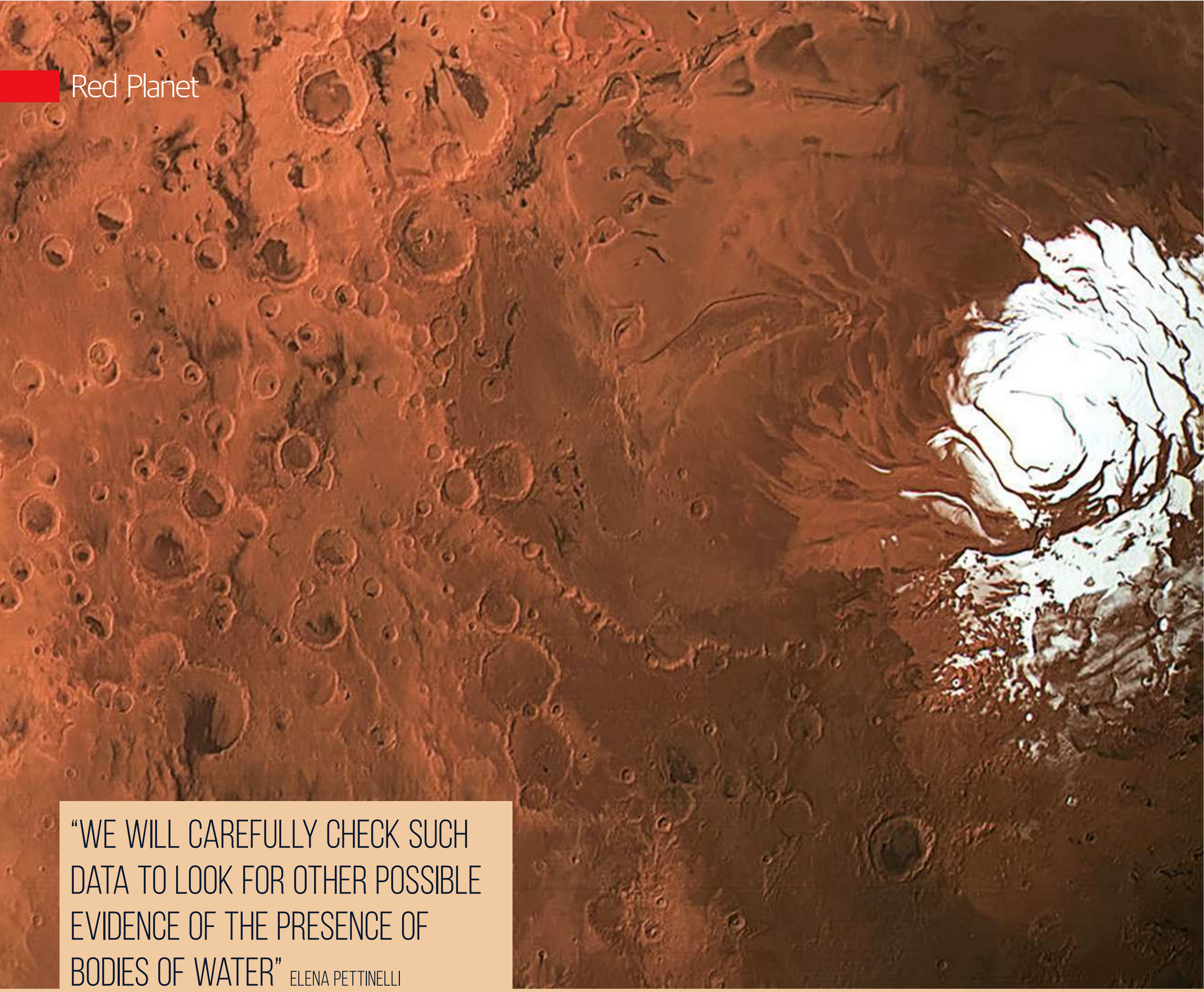
In discovering the first aurora in the upper atmosphere, MAVEN has also shown how solar storms have aided and abetted that loss to space. The enhancement implies that they may have been large enough to have been the determining factor in the overall loss rate in the ancient past. "Solar storms were larger and occurred more often early in history," says Jakosky. "They may have driven the overall loss rate."

Orbital missions have also found that the upper atmosphere is a lot 'friskier' than previously thought. The next arrival, the Hope orbiter, launched in July 2020 by the United Arab Emirates (UAE), will add to that understanding. Hope's instruments will get the 'synoptic view' – a larger overview, fitting in with other missions where there are gaps in knowledge.

More recently, instruments aboard the Trace Gas Orbiter have watched how the minute amounts of water vapour on present-day Mars have reached higher altitudes in greater amounts during global dust storms. The question of how exactly local dust storms 'go global' remains another mystery.

"It may be that dust storms on Mars are basically chaotic," says Dr Claire Newman, an atmospheric specialist at Aeolis Research in California, who is working across several current missions. "A slight year-to-year difference in the availability of surface dust or local surface wind patterns might make the difference between a global storm or nothing at all."

Due to arrive at Mars on 9 February, the Hope mission will examine the coupling between the lower and upper atmosphere – the exchange of atmospheric energy and mass. "This was highlighted from MAVEN observations as being important," notes Jakosky.



“WE WILL CAREFULLY CHECK SUCH DATA TO LOOK FOR OTHER POSSIBLE EVIDENCE OF THE PRESENCE OF BODIES OF WATER” ELENA PETTINELLI

“Hope will, by making simultaneous observations of the lower and upper atmosphere and by using synoptic measurements of the lower atmosphere, help better understand atmospheric dynamics and the energy transfer.”

The forecast for Martian meteorologists is looking good. InSight has the most sophisticated weather-measuring instruments ever sent to Mars. To date, Murphy's law has brought bad luck in obtaining decent wind measurements on earlier missions.“Wind is crucial to so many things on Mars,” notes Newman. “That includes how the surface erodes and changes over time.” Atmospheric scientists also need wind measurements to calibrate their understanding of how localised flows feed into the overall global circulation of the planet. She adds: “Having the highest rate of pressure data” – up to 20 measurements a second on InSight – “has also opened up a whole new world on turbulent variations.” The main area of interest is just how different levels in the atmosphere connect with each other. “We've known for a while that we don't quite understand how dust, once it is lifted from the surface, ends up producing high-altitude dust layers, even during the ‘clear’ season when no major dust storms occur.”

Such measurements will also help in understanding how climate has evolved on Mars. How the Martian atmosphere has changed is inextricably linked with the question of water. The most intriguing insights in recent years have come from itinerant rocks which have been flung from the Martian surface in the ancient past. As remarkable as it sounds, an estimated half a tonne of the Red Planet arrives here on Earth every year. In particular, one remarkable meteorite landed in the Sahara Desert in 2011, and is usually known as ‘Black Beauty’ to those who have examined its various fragments.

It is hardly a Rosetta stone, rather an amalgamation of material that has been blasted and fused together on the surface of Mars. Analysis has shown it is made up of a jumble of fragments – ‘a hopeless mess’ in one assessment – which have fused together at different times throughout the planet's geological history. “The idea is that this meteorite is made up of breccia,” says Dr Jane MacArthur of Manchester University, who studied it for her PhD. “That is, it consists of lots of broken fragments in a fine-grained matrix.”

Meteorite falls have been described as the only free lunch in planetary astronomy. To carry on that analogy, researchers have no idea who the chef was, what ingredients were used or even which shift they were working on. Regarding Black Beauty, what we're

## WATER IN BLACK BEAUTY

The various elements of the ‘Black Beauty’ meteorite – discovered in the Sahara Desert in 2011 – show a range of ages of material which fused together on the Martian surface. Most recently, a team in Tokyo has analysed minerals and chemistry in one part of the rock which show there was water present on or in the Martian crust 4.4 billion years ago during an impact which melted part of the crust.

**Left:** Wind has shaped the visible surface of the south polar ice cap, and beneath the surface it has been suggested there may be 'lakes' of liquid water

© ESA

trying to do is unravel all the component parts in MacArthur's assessment.

It is unusual in that it is clearly composed of rocks which have been excavated near the surface and not from deep within the interior. As such, Black Beauty shows how the crust and the atmosphere have interacted over time. In places, its youngest material – roughly 1.5 billion years old – contains ten-times more water than other Martian meteorites. Taken at face value, this suggests much more water has flowed on the Red Planet in the recent past than was previously believed. But is there liquid water on Mars today?

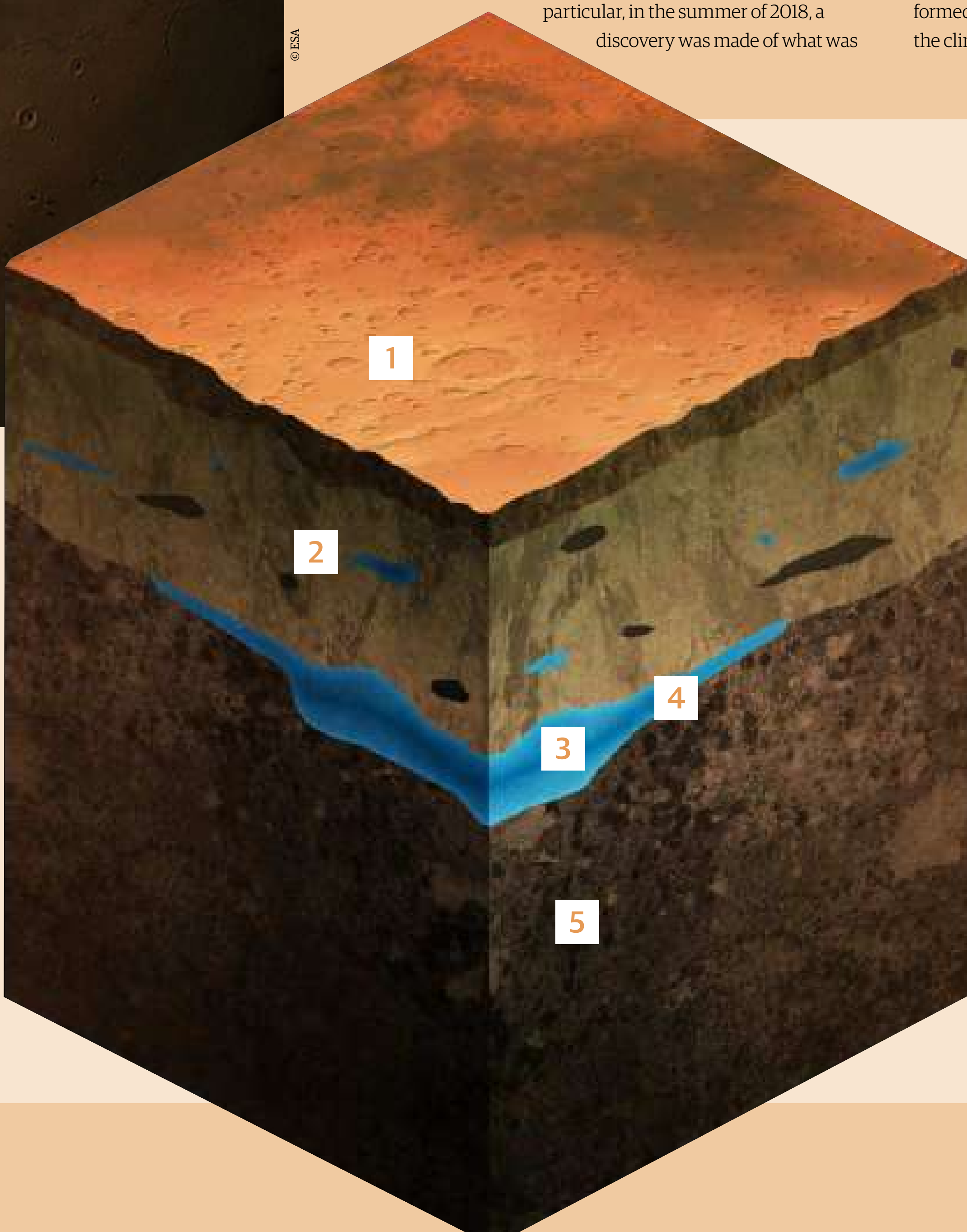
If there is, it will have long since frozen beneath the planet's surface in an extensive aquifer. So far the inference of subsurface ice has been made from radar measurements taken from orbit. Radar signals penetrate the surface, and their reflection indicates the presence of ice in several places. In particular, in the summer of 2018, a discovery was made of what was described as a large lake under the south pole. What lead scientist Dr Elena Pettinelli of Roma Tre University called "anomalously bright subsurface reflections" were observed by a radar instrument on the Mars Express orbiter.

Now, two years later, greater numbers of passes by the same instrument have refined the observations. A total of 134 'profiles', as the team calls the radar observations "are crossing each other and covering a larger area". Centred on what they interpreted as a lake, a different analytical technique has now been employed. This, the team points out, is the exact same procedure used to look for subsurface water under terrestrial ice sheets in polar regions.

"We have analysed the radar signals looking for specific features that on terrestrial radar are associated with the presence of liquid water at the base of the ice sheets," says Pettinelli. This new approach implies that subglacial meltwater was formed elsewhere on Mars in the ancient past, when the climate was more clement.

## WATER AT THE POLES

**Mars today is freezing, with no signs of liquid water on the surface. But repeated passes over the south pole of the planet by the Mars Express radar instrument have shown that there may be 'lakes' underneath them, increasing the likelihood of life being present.**

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## WATER ON MARS

**1 DRY SOIL**
Martian soil forms a dusty layer. It's made up of nutrients such as sodium, potassium, chloride and magnesium.

**2 SIGNS OF ICE**
Ice which once formed on the surface of Mars is thought to have become buried, leaving an immediate permafrost subsurface with young ice in its pores.

**3 POCKETS OF WATER**
Water ice is locked within cavities across the mid-latitudes of the planet. Some chunks of frozen water have been found just beneath the surface.

**4 SUBSURFACE RESERVOIRS**
Underground lakes are thought to exist far beneath the surface. A high level of salt or heat from Mars' interior could even result in them being liquid.

**5 THE FOUNDATION**
The water would lie above an impermeable bedrock, which has a high concentration of sulphur.

The findings are controversial. Some believe the observations are more to do with how the radar is modelled. Others think the water would be more sludgy and is perhaps a subsurface layer of high groundwater abundance. Water would have to be very salty and heated to stay warm.

The Italian team acknowledges there is no current explanation for any subsurface heat sources on Mars, unlike Antarctica, which hosts several subsurface lakes which are kept above freezing. Hypersaline water could also remain above freezing. "We think that perchlorate salts, that are ubiquitous on Mars, could help to keep the water liquid," Pettinelli says. "We will carefully check such data to look for other possible evidence of the presence of bodies of water."

All these questions are the curtain raiser for the next decade, when space agencies will attempt to return samples from Mars. The Red Planet is evidently a complex world – no less complex than our own, even though it doesn't have plate tectonics or an ocean. "Mars is also an excellent place to study planetary processes that tell us about habitability and the potential for life, the evolution of climate and the atmosphere and the evolution of a terrestrial planet during its first billion years," concludes Jakosky. "It's a compelling planet, with lots left to explore to find answers to major questions."

## DUST STORMS

In 2018, one of the most fierce global dust storms on Mars covered the planet. Spacecraft watched how the dust fed into the atmosphere, enhancing the amount of atmospheric water vapour taken to the upper atmosphere, which is then broken down and lost to space.


**Nicholas Booth**
*Space science writer*
Nicholas worked on *Astronomy Now* and served as a science writer for national newspapers. He co-wrote *The Search for Life on Mars.*

**Elizabeth Howell**
*Space science writer*
Elizabeth holds a PhD in aerospace sciences and is a contributing writer to **Space.com**. She co-wrote *The Search for Life on Mars* with Nicholas Booth.

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**Opposite:** Over the next decade, samples will be taken by the Perseverance rover in Jezero crater and left as caches to be picked up by a later 'fetch' rover for return to Earth

**Below:** Dust storms on Mars can whip up and cover the whole of the surface. This was the view in 1971 when Mariner 9 – the first successful orbiter – arrived. As the dust cleared, the giant volcanoes were seen for the first time

© NASA/JPL

# 2021 ONWARDS: PLANS FOR STUDYING THE RED PLANET

On 9 February 2021, the UAE's Hope mission – a small test orbiter – arrived at the Red Planet, carrying mainly American instruments. Next the Chinese Tianwen-1 mission will enter a long, looping orbit. A few months later a lander will be dropped from the orbiter, which will see the starting gun on China's own ultimate ambitions to return samples – as it has just done from the Moon.

NASA's Perseverance landed on Mars on 18 February. Along with other scientific objectives, it will be looking for signs of past life on the Martian surface. The mission will land come what may. It will barrel straight in, aiming at a bullseye 45 kilometres (28 miles) across: Jezero crater. The good news is that NASA has done this before. The bad news is that two European landers have crashed in this same region already – Beagle 2 and Schiaparelli. There will be the sky crane that drops it down and the 'seven minutes of terror' as NASA waits for the signals to confirm a successful touchdown.

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### ROSALIND FRANKLIN

This European rover – built in Stevenage – will be taken down to the surface by the Russian Kazachok lander. Because of problems with its parachute systems and complications from the coronavirus pandemic, its launch has been pushed back to the autumn of 2022. Both lander and rover will land in Oxia Planum in the spring of 2023.

© ESA

### TERA-HERTZ EXPLORER (TEREX)

The Mars Terahertz Microsatellite is a Japanese mission designed to take both an orbiter and lander to Mars. The latter will measure oxygen isotope ratios in the atmosphere to better understand the chemical reactions that replenish the Martian atmosphere with carbon dioxide.

© TEREX

### MANGALYAAN-2 (MARS ORBITER MISSION 2)

India's follow-up mission to its first orbiter may carry a lander and rover as possible additions. While there is no official announcement of when it will be launched, it will likely be in 2024 at the earliest.

Source: Wikipedia Commons © Nesnad

### MARTIAN MOONS EXPLORATION (MMX)

Japan plans to send a probe to Mars' largest moon Phobos in 2024. It will drop a small lander on Phobos, collect samples and return them back to Earth. The samples are expected to arrive in July 2029.

© NASA

### MARS SAMPLE RETURN

After launch in July 2026, a lander will carry its own Mars ascent rocket for the return journey, as well as a 'fetch' rover. This will land in Jezero crater in August 2028, as close to Perseverance as possible. The rover is a 'minicab' designed to retrieve the samples and take them to the ascent rocket, which will fire into low-Mars orbit with the sample-return canister in spring 2029. A European-built orbiter will 'catch' the canister with the samples inside it and then transfer them to a return mission, which will land back on Earth some time in 2031.

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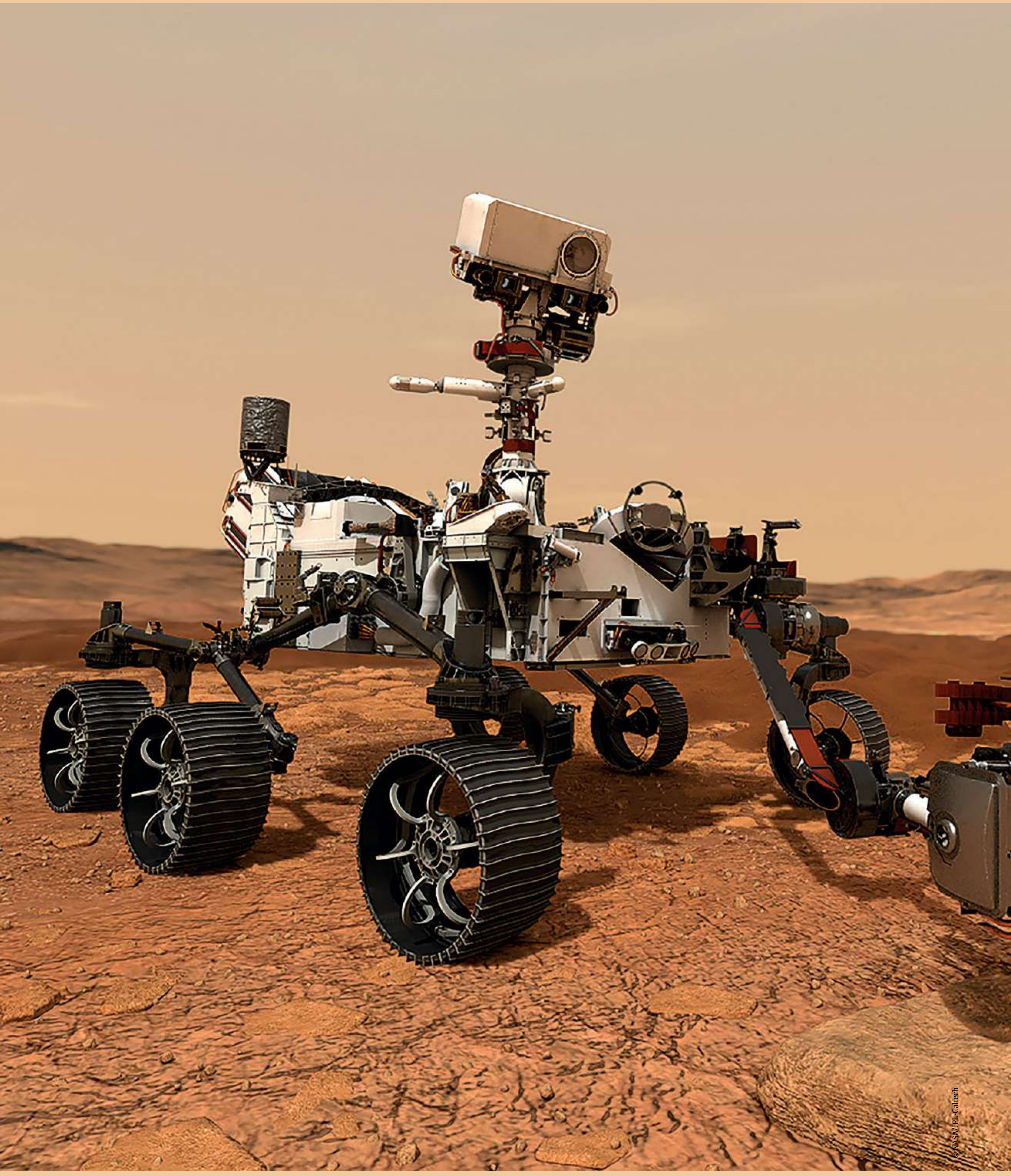
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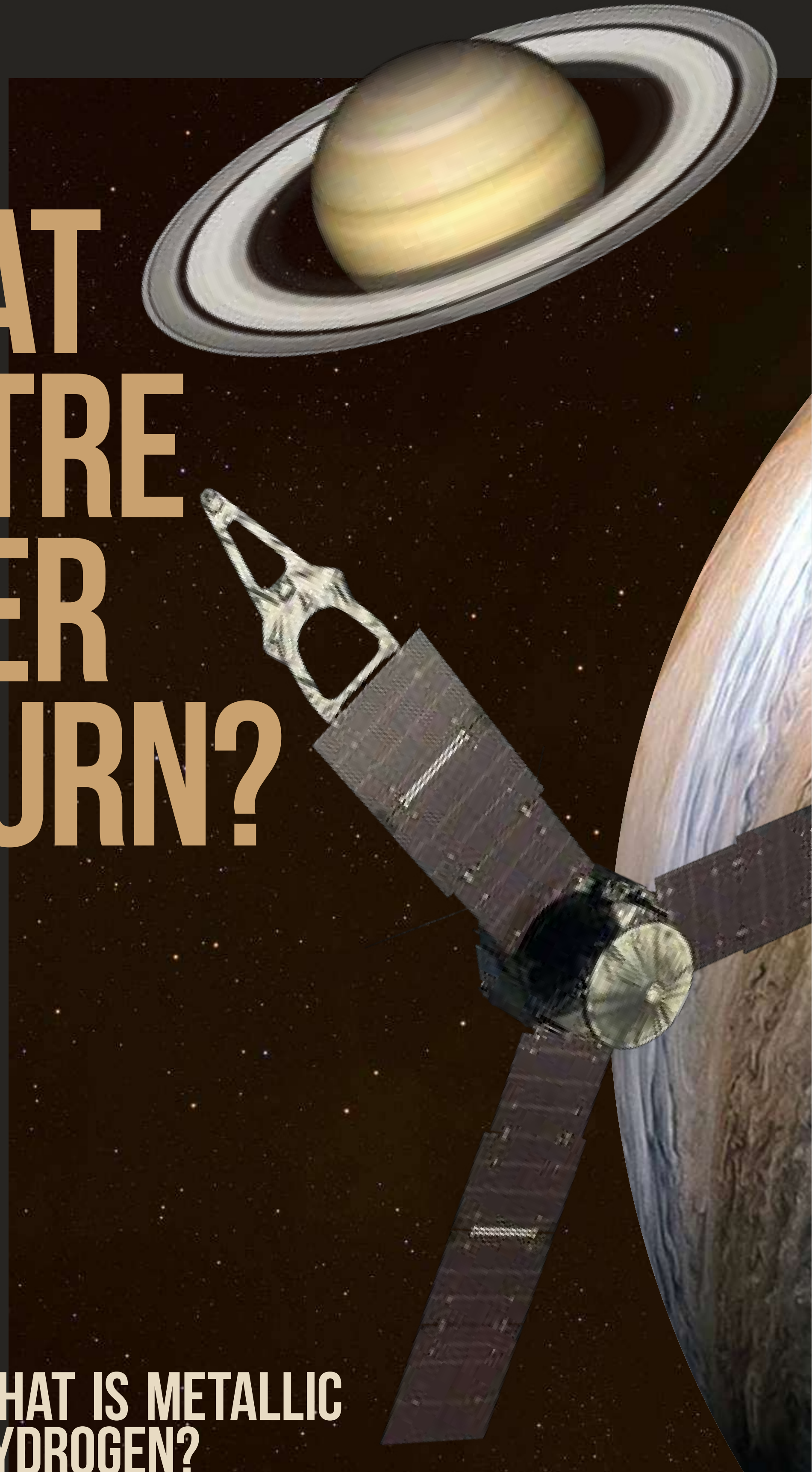
MYSTERY SOLVED?

# WHAT'S AT THE CENTRE OF JUPITER AND SATURN?



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## With the help of AI, planetary scientists may have finally been able to put an age-old puzzle to bed

**Reported by Leo Bear-McGuinness**

Of all the planets in our Solar System, Jupiter and Saturn are perhaps the most mischaracterised. Known as gas giants, many may naturally assume that these two behemoths consist of nothing but gas and clouds to their cores. While it's true that they mostly contain hydrogen and helium, these giants are much more than the Milky Way's two big balloons. Thanks to their phenomenal sizes, the planets accrue enough heat and pressure to compound their gases into liquid states. Under these unearthly conditions, helium and hydrogen flow in great seas just below the outer gaseous layers of the planets. Jupiter, the larger of the two giants, is thought to be home to the largest ocean in the Solar System – one made of pure hydrogen.

"Jupiter and Saturn are mostly made of hydrogen and helium, and this is the reason they are known as gas giant planets," says Ravit Helled, a professor in the department of astrophysics and cosmology at the University of Zürich. "However, the interiors

## WHAT IS METALLIC HYDROGEN?

### 40,000

The estimated depth, in kilometres, of Jupiter's metallic hydrogen layer. This is equivalent to about 24,850 miles.

### MORE HELIUM, LESS METAL

Helium stabilises the hydrogen molecules inside gas planets, delaying the onset of metallisation.

### THE TRADITIONAL MIDDLE TIER

In traditional models of gas planets, metallic hydrogen made up the inner layer. This distinction is now thought to be more fluid.

### AN OLD IDEA
The metallisation of solid hydrogen was first predicted in 1935.

### FIVE PHASES
Five non-metallic, solid phases of hydrogen have been identified so far, but more might be found in the future.

### NOT SOLID PLANETS
Given their known conditions, it was thought that solid hydrogen couldn't be formed in the core of giant planets.

### KEY TO MAGNETISM
Metallic hydrogen is thought to be the conducting material key to the gas planets' magnetic fields.

### SUPER-METAL
Metallic hydrogen was theorised to be a superconductor at room temperature in 1968.

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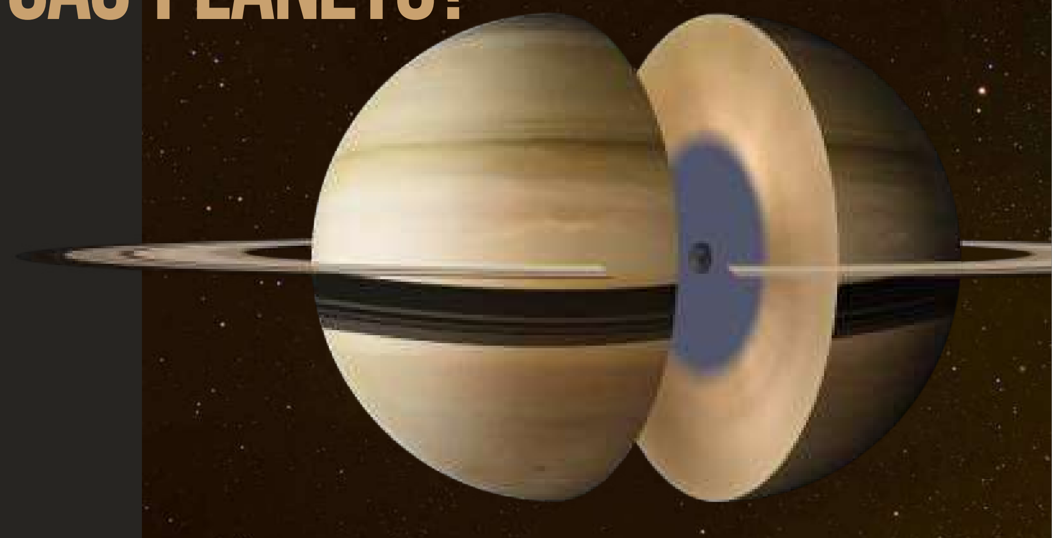
## WHAT'S INSIDE THE GAS PLANETS?



**AMMONIA ($NH_3$)**
Clouds of ammonia and water are thought to shroud the surfaces of Jupiter and Saturn.

**WATER ($H_2O$)**
Recent results from NASA's Juno space probe suggest that these ammonia-water clouds can conduct 'shallow' lightning and rain slushy ammonia-rich hailstones.

**HYDROGEN**
Together hydrogen and helium account for about 85 per cent of the total mass of Jupiter and 75 per cent of the total mass of Saturn.

**Above:** After orbiting the planet 22 times, the Cassini probe ended its mission and plunged into Saturn on 15 September 2017

of the planets are not in the gaseous phase due to the high pressures. Therefore you should think of giant planets as being fluid, and not gaseous."

But these fluids aren't uniform. Below the great oceans of hydrogen, the gas is thought to turn to metal. Under such intense pressures, the electrons of hydrogen atoms are assumed to rip apart from their companion protons. And with these electrons now free to conduct energy, the liquid seas of hydrogen are thought to turn metallic.

This remarkable alchemy has had physicists intrigued for decades. If researchers knew just a little bit more about the transitions between these different states of hydrogen and helium, it could significantly advance their understanding of these gassy titans. "Progress in our understanding of hydrogen and hydrogen-helium at planetary conditions can be used to further constrain structure models of the planets," Helled tells **All About Space**. "The fact that helium can separate from hydrogen, resulting in helium rain in giant planet interiors, is critical to understanding their evolution and internal structures. And the fact that hydrogen metallises explains the strong magnetic fields in these planets."

And planetary scientists aren't the only ones interested in furthering our understanding of metallic hydrogen. Aside from being a fascinating state of matter within the gas giants, the metal is also thought to have multiple practical uses. Thanks to its free electrons, it's theorised that solid metallic hydrogen could be a superconductor at room temperature. If isolated and stabilised on Earth, it would be one of the most efficient materials on the planet for transferring and storing energy. The latter trait could even enable the metal to be used as a highly efficient rocket fuel. Given its potential to launch a whole new era of power, technology and space exploration, there's an understandable interest in learning more about the metal's properties.

Sadly, it's not yet possible to wade through the clouds and seas of Jupiter and collect a beaker of metallic hydrogen for further research. Physicists have had to get a bit more creative. Some have tried to recreate the high pressures of Jupiter and Saturn here on Earth in an attempt to engineer their own metallic gases. Just three years ago, two researchers at Harvard University claimed to have succeeded. After squeezing the gas in between two tiny diamonds at a temperature just above absolute zero, the physicists reported in the journal *Science* that their hydrogen sample became shiny and reflective. However, before this sample could be further tested to check if it really was metallic hydrogen, it was lost. And once you lose a microscopic sample of hydrogen, there's apparently not much point attempting to find it…

Somewhat expectantly, this experiment and its claims were greeted with a dose of healthy scepticism from the scientific community. "To probe this transition, people have been using various techniques," says Dr Bingqing Cheng, a computational physicist at the University of Cambridge. "For example, you can squeeze the liquid hydrogen between a diamond and then press and see what happens, or there are some laser-based techniques. But all these studies have a problem: it's very hard to characterise the material under high pressure. We know that this phenomenon transition happens, but experimentally it's very hard to locate."

Are there any more reliable ways of studying metallic hydrogen? Computational physicists like Cheng seem to think so. "The gold standard is always 'seeing is believing'. If something can be done in an experimental lab, that's sort of the ultimate proof," she tells **All About Space**. "But in this situation the experiments are so hard, and it's probably not getting much better in the near future, so theory plays a crucial role there."

The idea put forward by Cheng and her colleagues is that if all the known characteristics of hydrogen could be inputted into a computer, and then that computer ran a simulation of the intense pressures and conditions present within Jupiter and Saturn, scientists may have a much more reliable way of studying metallic hydrogen without ever moving from their laptops. The

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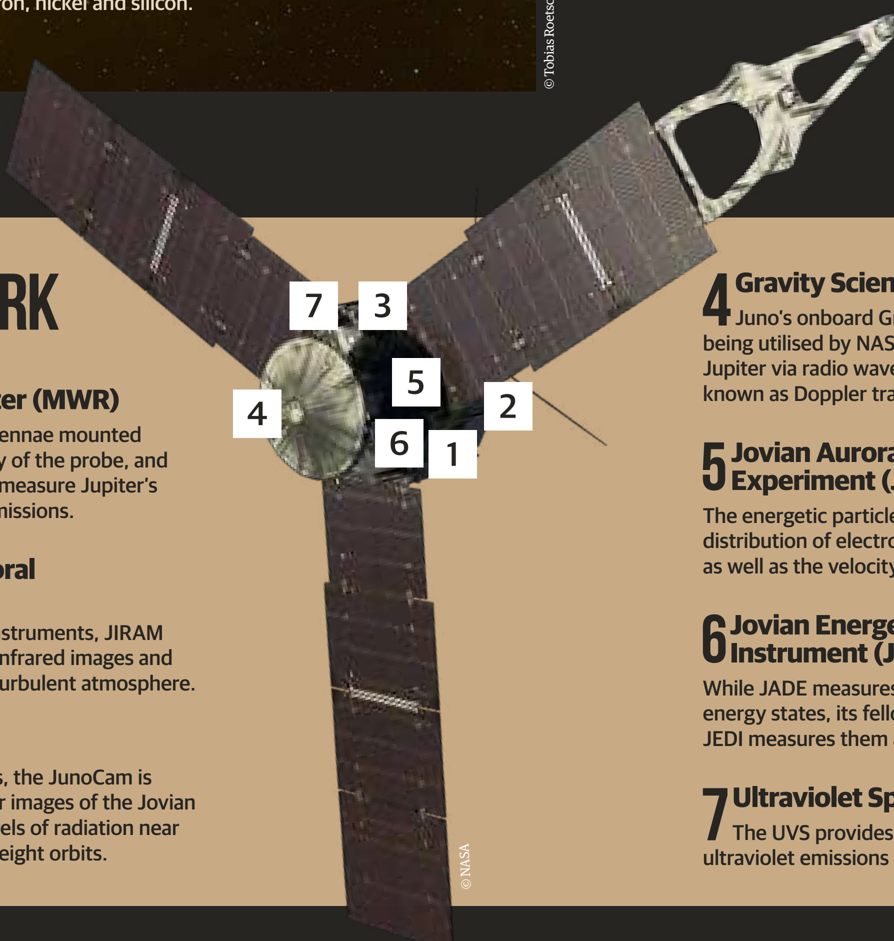
only snag is that such simulations would take an ungodly amount of computational power. "Even with the state-of-the-art method we are limited to a few hundred atoms, as well as a picosecond [one trillionth of a second] timescale," says Cheng. "And that is problematic when we are probing a phenomenon such as phase transition, which inevitably requires a large system. The machine-learning potential enabled us to achieve that."

And these machine-learning techniques appear to have done the job. In her research, Cheng and her colleagues announced that they had developed a way of simulating atomic phase changes using artificial intelligence and quantum mechanics. As the machine learning could 'learn' the potential energies and interatomic forces from reference calculations, it could then predict the immediate changes the 1,700 or so atoms would undergo when submitted to a broad range of temperatures and pressures. Without having to wait millions of years for a result to compute, Cheng's team managed to map the entire phase diagram of dense hydrogen. After processing the data, they found metallic hydrogen undergoes a continuous transition from molecular to atomic states in the liquid phase, with no first order transition observed above the melting line. In other words, the fluid-to-fluid transition is, in fact, fluid.

While this nebulous boundary between the molecular-hydrogen and metallic-hydrogen layers of gas planets had been guessed at by some physicists prior to Cheng's study, her team's results have helped confirm, theoretically at least, that the tiers of Jupiter and Saturn

# JUNO AT WORK



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## 1 Microwave radiometer (MWR)
The MWR comprises six antennae mounted on two of the sides of the body of the probe, and is used by Juno's operators to measure Jupiter's atmospheric circulation and emissions.

## 2 Jovian Infrared Auroral Mapper (JIRAM)
One of Juno's most versatile instruments, JIRAM has been designed to acquire infrared images and study the spectra of Jupiter's turbulent atmosphere.

## 3 JunoCam (JCM)
One of Juno's main imagers, the JunoCam is capable of taking visible-colour images of the Jovian cloud tops. Due to the high levels of radiation near Jupiter, it's only set to survive eight orbits.

## 4 Gravity Science (GS)
Juno's onboard Gravity Science equipment is being utilised by NASA to test the composition of Jupiter via radio waves. It does this via a process known as Doppler tracking.

## 5 Jovian Auroral Distributions Experiment (JADE)
The energetic particle detector, JADE, measures the distribution of electrons in the Jovian atmosphere, as well as the velocity and composition of ions.

## 6 Jovian Energetic Particle Detector Instrument (JEDI)
While JADE measures ions and electrons at low energy states, its fellow energetic particle detector JEDI measures them at high energies.

## 7 Ultraviolet Spectrograph (UVS)
The UVS provides Juno with the ability to detect ultraviolet emissions from the atmosphere.

are not finite. Unlike the rigid crust, mantle and core classifications of Earth's interior, the inner structures of the gas giants instead stay true to their hazy nature.

"A previous assumption was that the transition is sharp," Cheng says. "To make an analogy: when boiling water, you see the temperature starts to increase, and then all of a sudden you start to have vapour. It's a very sharp transition. But it's also easy to imagine that when this happens, the volume of the density changes suddenly. But actually, if you boil water at very high pressure in the super-critical region, this transition would happen smoothly.

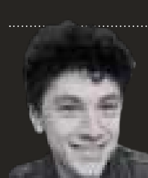
"Our simulation basically suggests that hydrogen-hydrogen actually sits in that super-critical region," she explains. "Take Jupiter, for example. If you dive into [it] from the surface, which has a low pressure, to the centre, you wouldn't see an abrupt change."

Unfortunately, there's currently no way to verify Cheng's results with an actual voyage into Jupiter's interior. But the few probes that have raked the surfaces of Jupiter and Saturn for data have made some key corroborating discoveries. Thanks to measurements taken by the Juno spacecraft, launched by NASA in 2011, astrophysicists now have further evidence that Jupiter's core has a fuzzy boundary, as its heavier elements appear to peel off for up to half its radius.

"Recent formation models and the available gravity field measurements of the planets from the Juno and Cassini missions indicate that the planets have complex interiors which include composition gradients and fuzzy cores," Helled tells **All About Space**. "Fuzzy-dilute cores can extend to a few tens of percents of the planet's total radius, and could also consist of lighter elements, such as helium and hydrogen."

On the surface of things, the existence of these fuzzy cores only further muddies the composition of the gas planets. But when combined with the results of Cheng's simulations, the picture of these giants actually becomes a lot clearer. Starting from a fuzzy core of known and unknown materials, the planets appear to bleed out their elements into their surrounding layers. These coats of metallic hydrogen, helium rain and molecular liquid hydrogen, each thousands of kilometres thick, are now thought to diffuse into each other, with no fixed boundaries. And all of these tiers, both distinct and hazy, are eventually capped off with a relatively thin covering of gaseous clouds of ammonia, methane and ice.

It's now more evident than ever just how otherworldly these other worlds are. "Juno really revolutionised our understanding of Jupiter," says Helled. "The mission is still ongoing, and we are looking forward to the new data. The Cassini mission revealed comparable information about Saturn. This is fantastic since we can now compare the two giant planets in our Solar System. While many questions remain open, this is a true golden era in giant planet exploration. The measurements of the ongoing Juno mission, the characterisation of many giant planets around other stars and the efforts in high-pressure physics provide new insights on the nature of hydrogen-helium-dominated planets."



**Leo Bear-McGuinness**
*Space science writer*
Leo holds a master's degree in science communication. He has written about space and science for a variety of magazines and websites.

**Right:** Jupiter, as captured by NASA's Juno probe during its eighth orbit



# HOW SPOOKY SCIENCE HELPS US PEER INSIDE THE PLANETS

**MICHELE CERIOTTI**

An assistant professor of computational science at the EPFL research centre in Lausanne, Switzerland, involved in the current research on metallic hydrogen.

**Could you explain how the machine-learning techniques used in your research work? Why were they preferable to standard computational methods?**

The idea is very simple - this is basically using a very flexible functional form to interpolate the predictions of the energy and forces acting on atoms, as obtained by solving the Schrödinger equation.

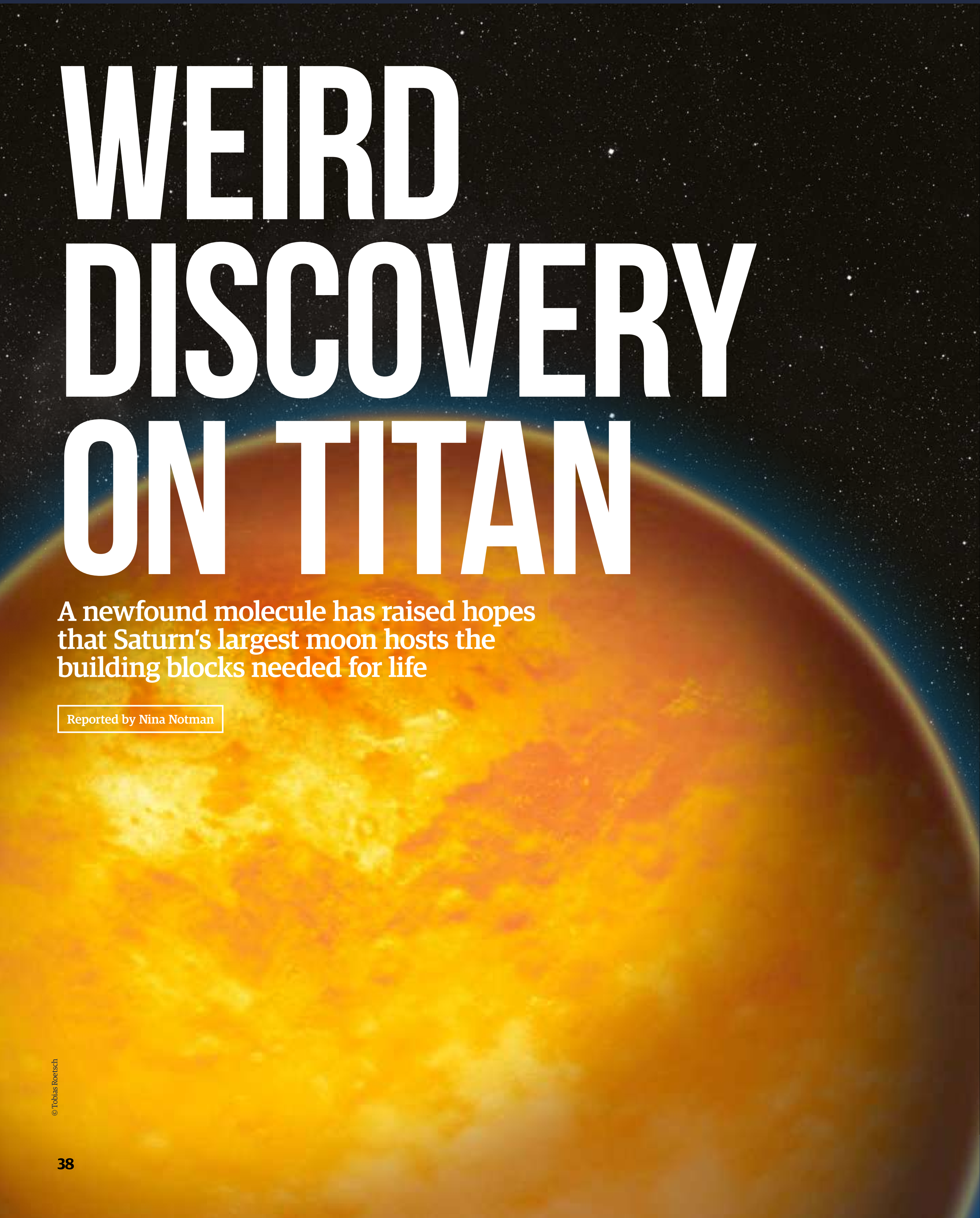
This basically gives you the same accuracy as the horribly complex - and computationally demanding - electronic structure calculations at a tiny fraction of the cost. This allows us to simulate larger systems for longer times, getting us closer to the behaviour you would expect from a macroscopic sample.

**How reliable are the results produced from such techniques? Could they be verified by other researchers, for example?**

These are definitely reproducible; we share all of the data that is needed to replicate our simulations. Errors may arise from two sources. One is the interpolation procedure. This we could test extremely carefully, so we are convinced we obtained the same accuracy as the explicit quantum calculations. The other are the quantum calculations themselves, that are also necessarily an approximation. This can't really be tested explicitly, but we compared three different kinds of approximations of the Schrödinger equations and obtained qualitatively equivalent observations, which is a strong indication the findings are robust.

**Which part of the research are you particularly proud of?**

What I like about this work is that it is the result of five years of effort in my group to combine machine-learning potentials with advanced statistical sampling techniques. I think often the technical effort that goes towards developing algorithms and methods is harder to receive the same level of recognition, so it is very satisfactory when you can show that all the hard work enables us to achieve scientific findings of great relevance.



# WEIRD DISCOVERY ON TITAN

A newfound molecule has raised hopes that Saturn's largest moon hosts the building blocks needed for life

Reported by Nina Notman

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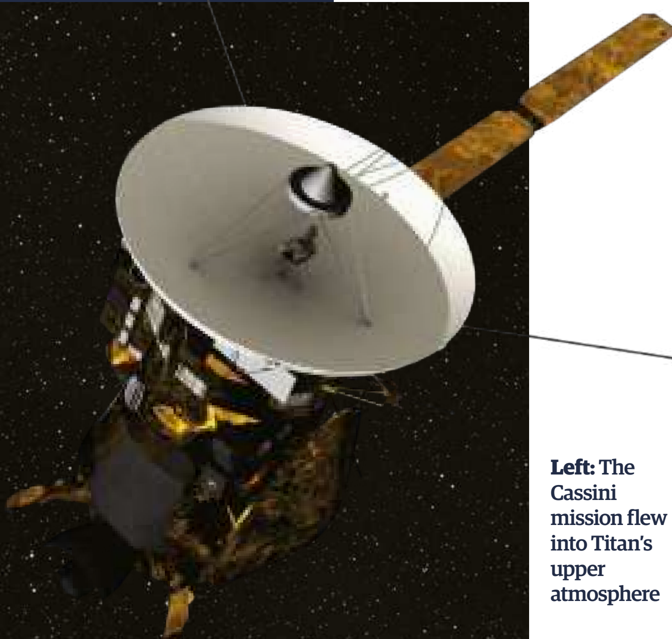


Are we alone in the universe? Humanity has been pondering the answer to this question for many years now, but no evidence has been found that we aren't – at least not yet. But it's not for lack of trying. Recent decades have seen us employ increasingly sophisticated telescopes and space missions in the search for alien life. We use tools able to listen out for radio and light messages that may be being sent from intelligent life forms. And other instruments are able to hunt celestial bodies, in our Solar System and beyond, for molecules that could potentially indicate the presence of any plant or animal life.

Saturn's largest moon, Titan, is an enticing location for molecule hunters. Both telescope measurements and space missions, most recently Cassini, have found that its atmosphere and surface are a treasure trove of organic molecules. These chemical compounds, composed of both carbon and hydrogen, form the basic building blocks of all living things on Earth. "We are looking for the LEGO blocks that you could use to build up more complex molecules," explains astronomer Conor Nixon from NASA's Goddard Space Flight Center.

Cyclopropenylidene is one such small organic molecule recently spotted by Nixon's crack team of molecule hunters. This finding was published in a paper in the *Astronomical Journal*. The finding of cyclopropenylidene is particularly exciting because it's the second structure with a closed loop to be found in this locality. The first was the six-membered ring benzene in 2003. Closed loops are exciting finds because the nucleobases – the A, C, T and G – which make up the rungs of the ladder in our own DNA molecules are themselves six-member rings. DNA is the code of life; it contains the instructions for the development and function of all living things.

Cyclopropenylidene is a triangle containing three carbon atoms and two hydrogen atoms. "It might be a lower level ingredient that you can use to build up these larger ring molecules," explains Nixon. "Finding it takes us a little bit closer to deciphering the organic chemistry that can lead to these larger, more complex things that could be even more life-like down the road."

"IT TAKES US A LITTLE BIT CLOSER TO DECIPHERING THE ORGANIC CHEMISTRY THAT CAN LEAD TO MORE COMPLEX THINGS" CONOR NIXON

Titan is similar to Earth in more ways than just hosting an abundance of organic molecules. It has a landscape that visually resembles ours, with plains and dunes, liquid rivers, lakes and seas, and a weather cycle with clouds and rain. There are also some notable differences. It is mind-numbingly cold, with a peak summer temperature of around -180 degrees Celsius (-292 degrees Fahrenheit). The atmosphere contains no oxygen and the surface liquid is a mixture of the hydrocarbons methane and ethane. The rain on Titan is also methane rather than water.

If Titan's surface harbours life, its lakes have been pinpointed by some as the most likely location. But surface life on Titan can't be life as we know it. It would be an exotic type of methane-based life that has been hypothesised to possibly breathe in hydrogen, rather than oxygen, and exhale methane, rather than carbon dioxide.

Finding life as we know it hasn't been ruled out for Titan though. There is strong evidence that large oceans of liquid water are sloshing around beneath its crust. These, astrobiologists suggest,

**Left:** The Cassini mission flew into Titan's upper atmosphere

## TITAN'S WEIRD MOLECULE

Cyclopropenylidene's presence in this location was highly unexpected

### It's a triangle

Cyclopropenylidene is a triangle of three carbon atoms with two hydrogen atoms hanging off it. Closed loops are important structures in the search for life.

### It's super friendly

Because of its triangular structure, cyclopropenylidene is highly unstable. It therefore seeks to join up with other molecules to form more stable structures.

### It's hard to spot

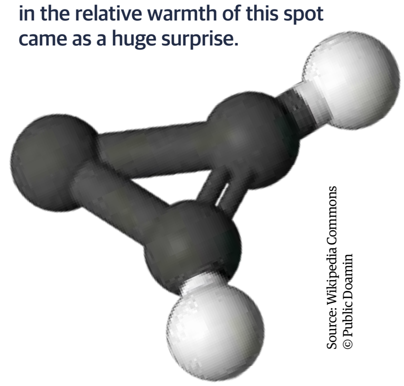
On Earth, cyclopropenylidene has never been seen out in the wild. It has, however, been produced in a laboratory.

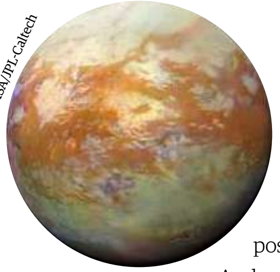
### It likes the cold

Cyclopropenylidene has been observed in the galaxy using radio telescopes. It frequents the extremely cold clouds of gas and dust that float between star systems.

### Found on Titan

Cyclopropenylidene has only been observed in one atmosphere: Titan's. Its presence in the relative warmth of this spot came as a huge surprise.

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may contain life in a much more recognisable form.

Alien life hunters keep an open mind to both possibilities: life as we know it and life as we don't. Either way, organic molecules are expected to be needed. Titan's outer atmosphere – where the cyclopropenylidene was found – is a location well known to have lots of chemistry going. "It's like a chemical factory," says Rosaly Lopes, a Titan expert at NASA's Jet Propulsion Laboratory (JPL).

Titan's atmosphere contains approximately 95 per cent nitrogen and five per cent methane. In the outer edges of the atmosphere, exposure to energy from the Sun and energetic particles in Saturn's magnetosphere drive reactions between the gases, generating a 'soup' of progressively more complex molecules.

A ground-based telescope array positioned high up in the Chilean Andes is a popular tool for hunting down these molecules. The Atacama Large Millimeter/submillimeter Array, better known as ALMA, is a radio telescope, meaning it looks at radio waves being given off by objects in space. This section of the electromagnetic spectrum is well known for holding the secrets of some of the coldest objects in the universe. "ALMA came online in 2011 and is a very powerful telescope that has been revolutionising our studies," says Nixon.

Atmospheric hunts such as Nixon's typically start out with predictions of organic molecules that might be hanging out there. Conjectures consider other molecules known to be in that location, the temperature of the area and how far apart the molecules all are from each other. Next, time on ALMA is negotiated. For some telescopes, such as Mauna Kea in Hawaii, astronomers go to the telescope and assist with their data collection. This isn't the case with ALMA. "We don't go and babysit the telescope; it's far too big and complex. Data is collected by specialist engineers who know exactly what they're doing," Nixon says.

Once collected, the data is searched for evidence of any of the predicted organic molecules. It's possible to positively identify molecules because every molecule produces a unique pattern in the electromagnetic spectrum. These so-called

# WHAT HAPPENS ON TITAN'S SURFACE?

**1. Nitrogen & methane leave the surface**
These two gases percolate up from the surface of Titan, eventually reaching its outer atmosphere.

**2. The gases combine**
Once in the outer atmosphere, the nitrogen and methane react to form small organic molecules such as cyclopropenylidene.

**3.They react again**
These organic molecules then grow larger by reacting with each other, and also other nitrogen and methane.

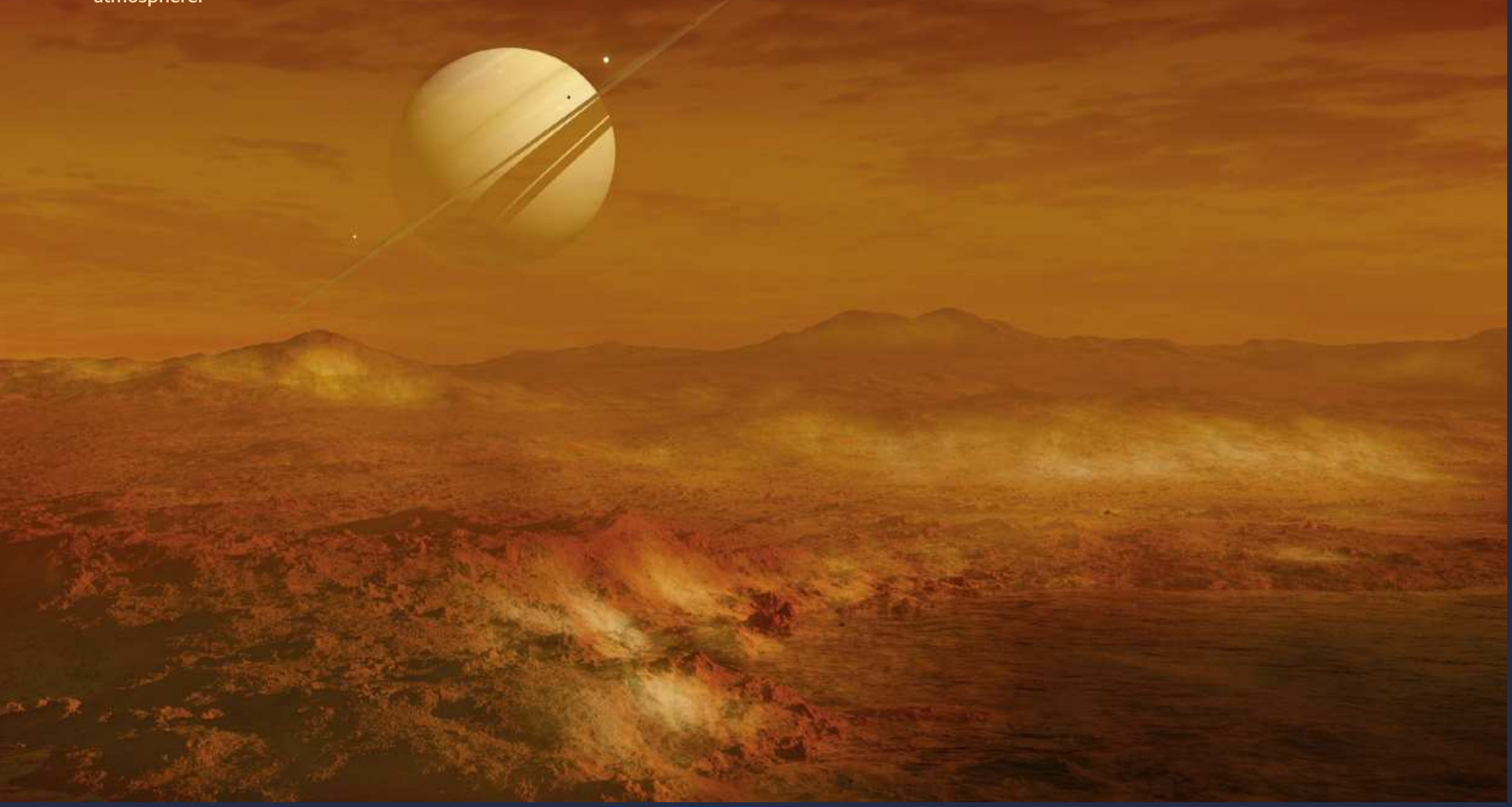
**4. Again and again**
These reactions keep happening, producing a soup of different organic molecules.

**5. The molecules sink**
The heavier molecules then sink towards the surface, clumping together as they do so.

**6. On the surface**
Eventually the clumps of molecules come to rest on Titan's surface. Their appearance is like that of sand.

**7. Forming new life?**
Once on the surface, it is possible that they go on to form methane-based life forms. Life as we don't know it.

**8. Or life as we know it...**
They may also somehow travel to the water under the surface where they go on to form water-based life forms.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molecular fingerprints are analogous with our fingerprints. Cyclopropenylidene wasn't actually on the list of molecules Nixon's team had expected to find. They were searching for some larger nitrogen-containing rings instead. "We didn't find those this time around, although I still have hope for the future. But we did find this cool triangular molecule instead, which caught us by surprise," says Nixon.

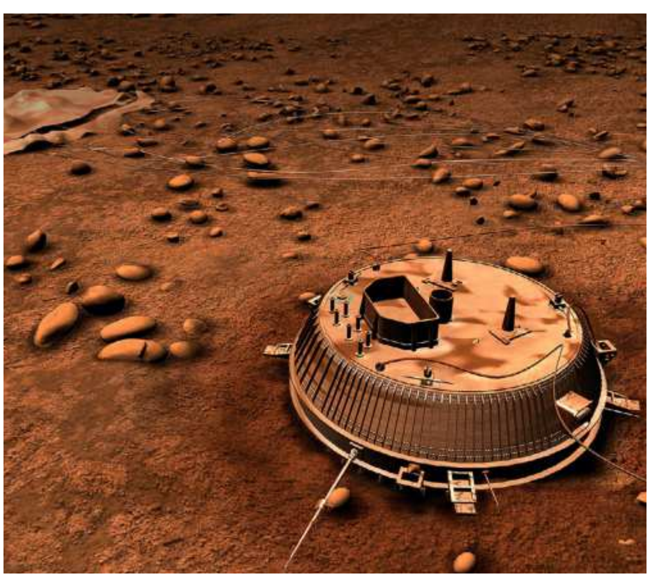
It wasn't only that they weren't looking for cyclopropenylidene at that moment, but astronomers had never planned to search for it in Titan's – or any other body's – atmosphere at all. This is because cyclopropenylidene isn't very stable. It loves to react with other molecules nearby to form more stable new molecules, so if it did form in an atmosphere, the expectation was that it would react again in the blink of an eye. In other words, it would be here and gone before we could possibly detect it. This little triangle has been found lots of times before in the galaxy, but only in the vast clouds of gas and dust that float between star systems. These regions are very cold and the molecules are large distances apart, hindering any onwards chemical reactions. In a warmer, far more tightly packed atmosphere, its lasting presence had seemed extremely unlikely.

Nixon's group spotted a second, less surprising but previously unseen organic molecule in the same location this year too: cyanopropyne. This finding was reported in *The Astrophysical Journal Letters*. Cyanopropyne contains four carbons, three hydrogens and one nitrogen and is straight rather than a closed loop. "This molecule is another of these larger hydrocarbon components that we've been looking for," explains Alexander Thelen, an astrobiologist colleague of Nixon's who led this study. In other words, another of the blocks that could potentially be used to build up life.

Michael Malaska, a planetary scientist at NASA's Jet Propulsion Laboratory, explains the importance of locating these small organic molecules in Titan's

**Left:** Infrared image of Titan created using 13 years of Cassini mission data

**Below:** An artist's impression of the Huygens probe on Titan's surface




# HOW TITAN HAS THE INGREDIENTS FOR LIFE

It's this moon's similarities to Earth that have drawn alien life hunters towards it

### 1. It has an atmosphere

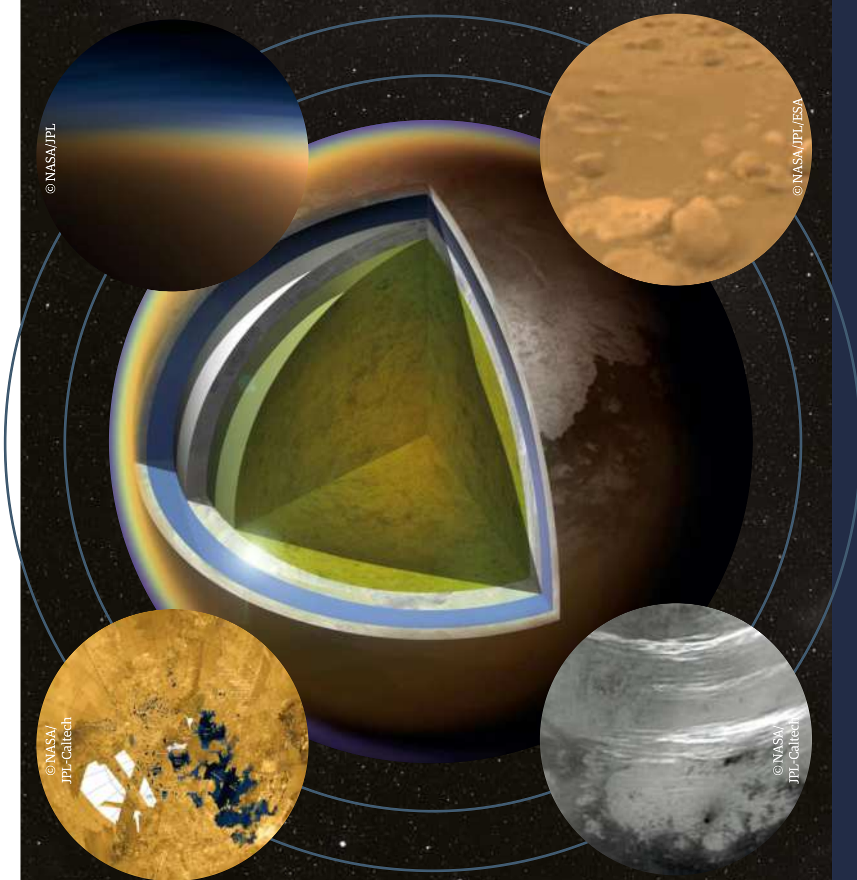
Titan has a thick, dense atmosphere that extends 600 kilometres (373 miles) upwards from the surface. This protects its surface from damaging radiation.

### 2. Titan has an energy source

Even though Titan is ten-times further from the Sun than Earth, it is believed to receive enough solar energy to sustain life.

### 3. Organic material exists on its surface

Titan has plains and dunes coated by organic material thought to have dropped down from its atmosphere. It's assumed the sea and lakebeds do too.




### 4. Liquid rests on its surface

About 60 per cent of the human body is water. Titan hosts liquid hydrocarbons on its surface that could potentially support an exotic life form.

### 5. It likely has water under its surface

It is thought that Titan has liquid water oceans deep under its crust. It is possible that these are inhabited by life as we know it.

### 6. Titan's weather

Titan has wind and rain that is able to transport organic material around its surface. This could potentially bring the ingredients needed to make life together.

**Atmospheric pressure**

Earth's atmospheric pressure is one bar. Titan's is a pretty comparable 1.5 bar.

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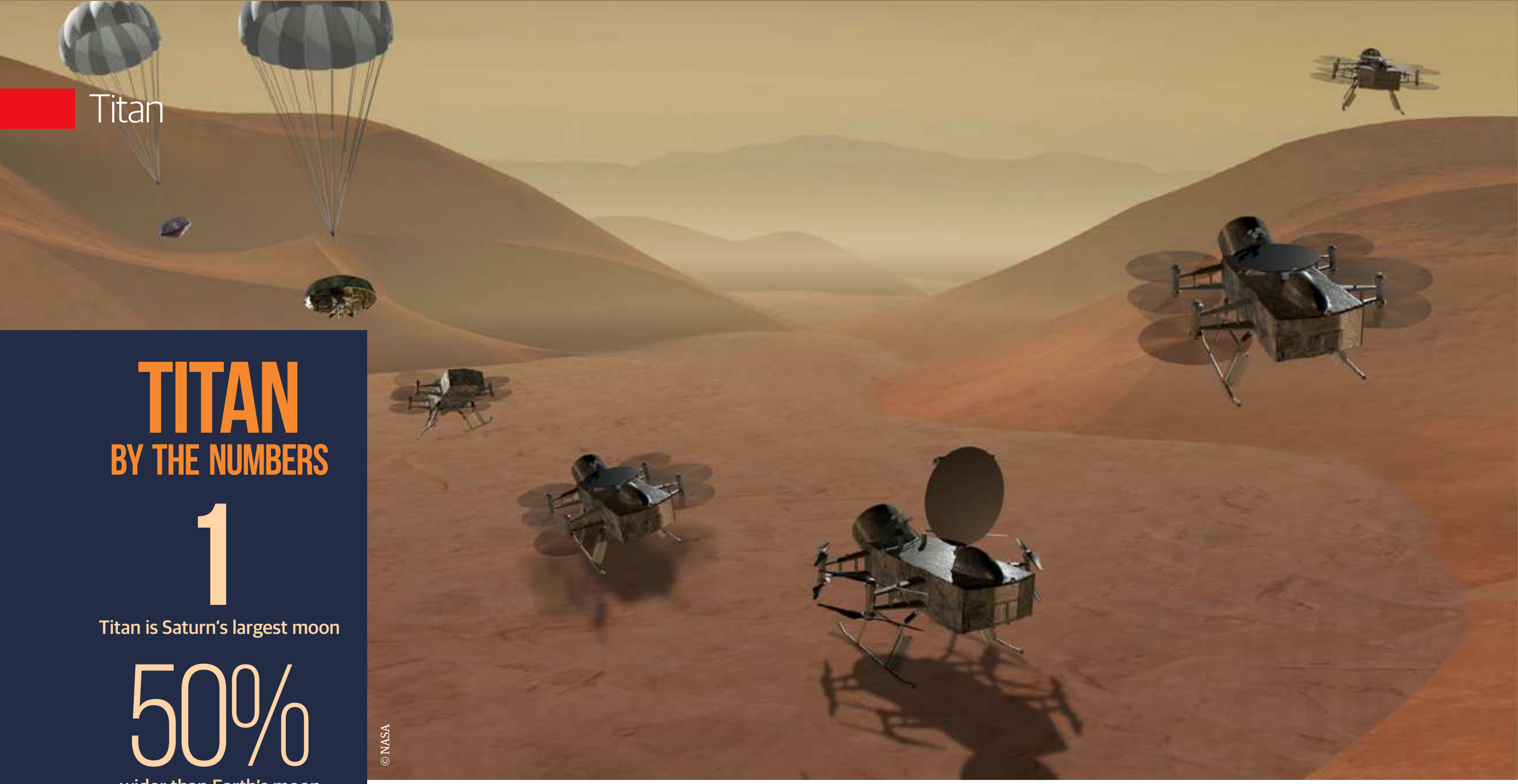
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# TITAN BY THE NUMBERS

**1**
Titan is Saturn's largest moon

**50%**
wider than Earth's moon

**80**
How many minutes light from the Sun takes to reach Titan

**600**
The depth of Titan's atmosphere in kilometres

**127**
The number of times Cassini flew by Titan

**90**
Minutes of data sent by Huygens once on Titan's surface

**1.5**
Titan's atmospheric pressure in bars

**2011**
The year the ALMA radio telescope started work

**Above: Dragonfly will be able to take off and land numerous times on Titan's surface**

atmosphere in a different way: "We are seeing the basic ingredients. It's like going into a kitchen and seeing chocolate chips, flour and walnuts, and knowing that you could potentially make a cookie out of this stuff."

As mentioned, these organic molecules keep reacting onwards, making larger and larger hydrocarbons. These then sink down towards the surface, clumping together as they travel. "They become these sticky, smog particles, similar to what we saw in the old days in the London pea-soup or in the Los Angeles city smog," explains Nixon. They then eventually land on Titan's surface. But Titan's thick, hazy atmosphere hinders observations. Much of the information we have therefore comes from the 127 flybys the Cassini spacecraft did of the moon, as well as the very short-lived Huygens probe that landed on its surface. Data from this mission is still being sieved through and is still throwing up some interesting findings.

A team led by Anezina Solomonidou at the European Space Agency (ESA) recently used this data to look at the material make-up of nine craters on Titan's surface in more detail than ever before. This work was then reported in the journal *Astronomy & Astrophysics*. As well as the composition of the craters, the scientists considered how they are evolving over time. "They found a lot of organic materials that have been deposited over the craters by wind," says Lopes. "From this we can infer that Titan remains a dynamic world today," adds Solomonidou.

NASA's Dragonfly mission will probe more of the surface of Titan in much more detail after its arrival at the moon in the mid-2030s. Dragonfly is a rotorcraft lander mission being developed at

> "WE CAN INFER THAT TITAN REMAINS A DYNAMIC WORLD TODAY"
> ANEZINA SOLOMONIDOU

Johns Hopkins Applied Physics Laboratory (APL) through the NASA New Frontiers Program. Its main goal is to investigate how far the cascade of organic chemistry reactions seen in the upper atmosphere progress once on the surface, especially when they've come into contact with liquid – either in the form of hydrocarbons or water that may have come up from below. "We want to see how complicated the prebiotic chemistry has got in a setting where liquid may have interacted with the organics that fizzled out from the sky," says APL planetary scientist and Dragonfly architect Ralph Lorenz. "We don't yet know how complicated things get when that soup has a long time to sit and stew."

The ultimate dream is that Dragonfly will spot chemical signatures that indicate that water-based or hydrocarbon-based life is present on Titan. Another hope among Titan experts is that a number of other missions will follow shortly behind Dragonfly, helping to reveal even more of the secrets of this mysterious, Earth-like world.


**Nina Notman**
***Space science writer***
Nina has a PhD in organic chemistry. She trained as a science writer on *Chemistry World* magazine before going freelance in 2012.

MYSTERIES OF THE UNIVERSE

# IS THERE A PLANET NINE?

**Mike Brown is the man who killed Pluto, but have the tables turned to leave his own theory of a ninth world in doubt?**

Reported by David Crookes

Mike Brown is a professor of planetary astronomy at the California Institute of Technology (Caltech), but he is also known as the 'Pluto killer'. It was 2006 when the International Astronomical Union downgraded Pluto's planetary status to that of a dwarf. Brown led the charge following his discovery of Eris in January the previous year, and it meant the Solar System was back to having just eight planets. For some, the move was unthinkable. Dr Alan Stern, who headed up the New Horizons mission that sent a spacecraft to Pluto, was particularly angry. Yet it had been coming since 1992, when a new object was discovered in what became known as the Kuiper Belt beyond the orbit of Neptune.

What few saw coming, however, was the emergence of a new candidate for the ninth planet. As if to rub salt in the wounds of those who felt Pluto's status should be reinstated, it was Brown – along with a fellow professor of planetary science at Caltech, Konstantin Batygin – who put the theory forward ten years later based on observations of six extreme trans-Neptunian objects, or ETNOs.

One of them, Sedna, is 40 per cent the size of Pluto, and it behaves in an odd way. Rather than forming an elliptical ring around the Sun as expected, this large planetoid in the outer reaches of the Solar System – some three-times farther away than Neptune – has an exceptionally long and elongated orbit. Taking about 11,400 years to complete its orbit, it will at some point be 76 astronomical units (AU) from the centre of our Solar System – that's 76 times the distance between Earth and the Sun – but it will swing out to more than 900 AU.

What's more, it's not alone. Brown and Batygin observed a cluster of six other ETNOs with similar orbits, and they tilt on their axis in the same direction. They don't appear to be as affected by the known giant planets in our Solar System as other trans-Neptunian objects, so the two scientists came up with an explanation.

According to Brown and Batygin's calculations and modelling, the unexpected clustering of objects is due to the gravitational pull of an as-yet-undiscovered ninth planet that is between 13 and 26 times farther out than Neptune. This hypothetical celestial body would have a predicted mass between five and ten times that of Earth. Its orbit would be elongated, ranging between 400 and 800 AU.

It's an exciting proposition, yet one that has not gone unchallenged. A study led by Kevin Napier at the University of Michigan has cast doubt on the theory. By observing 14 far-off rocky bodies discovered by three surveys – five each from the Dark Energy Survey and the Outer Solar System Origins Survey and a further four picked up by astronomers Scott Sheppard, Chad Trujillo and David Tholen – they say there is no

"IT WOULD HAVE BEEN MORE EXCITING IF OUR FINDINGS SHOWED STRONG EVIDENCE FOR CLUSTERING, AND THUS FOR PLANET NINE" KEVIN NAPIER

# PLANET NINE BY THE NUMBERS

**5-10**
times the mass of Earth

**2-4**
times the radius of Earth

**400-800**
times farther from the Sun than Earth

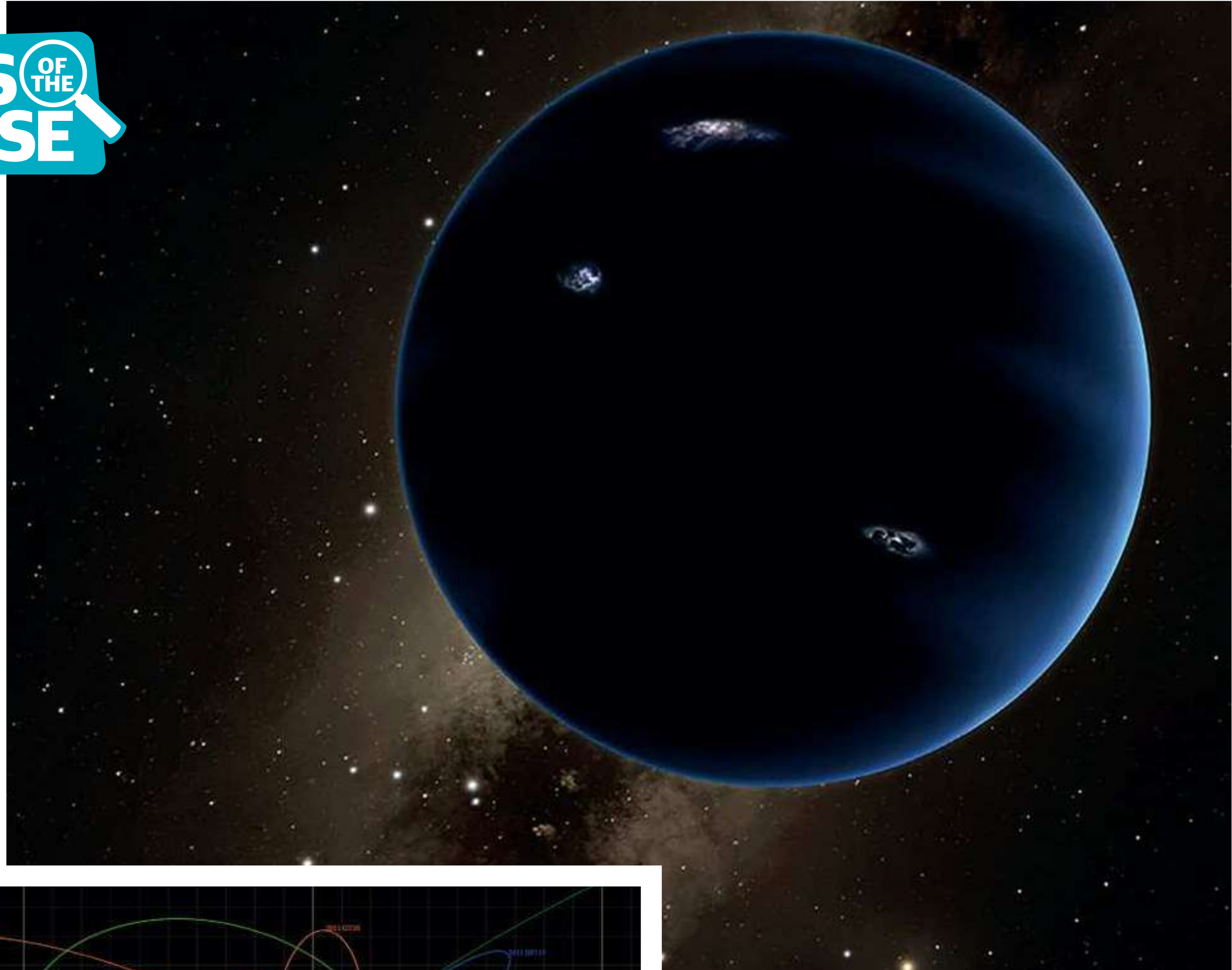
**0**
Number of observations

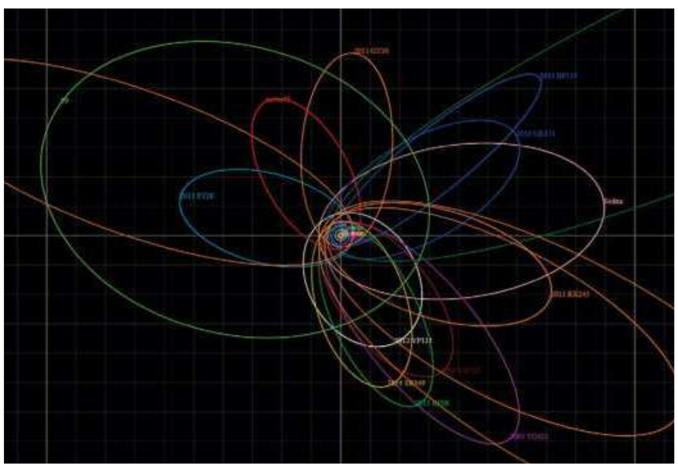
**6**
Number of extreme trans-Neptunian objects which appear affected by Planet Nine

**10,000-20,000**
Years to make a full orbit of the Sun

**20 YEARS**
Time Mike Brown estimates it would take for a probe to reach the planet

**0.2-0.5**
The hypothesised eccentricity of Planet Nine's orbit





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**Top:** An artist's concept of Planet Nine in orbit far from the Sun

**Above:** The original six ETNOs used by Brown and Batylin to hypothesise about Planet Nine, along with the planet's theorised orbit (in green) and eight other ETNOs

evidence of ETNO clustering that would firmly indicate the existence of an extra planet.

Instead, they say the findings by Brown and Batygin are due to observational bias. In other words, the new research reckons that Planet Nine's apparent existence is mainly based on the direction in which the two scientists' telescopes looked. Since Brown and Batygin observed just a small section of sky, the selection of ETNOs was limited. This, says Napier, weakens the case.

"Simulations have shown that Planet Nine causes the orientations of the ETNOs' orbits to cluster on timescales comparable to the age of our Solar System," Napier explains to **All About Space**. "There are now on the order of a dozen known ETNOs that appear to exhibit this clustering, and if you look at the data, the clustering appears to be rather robust.

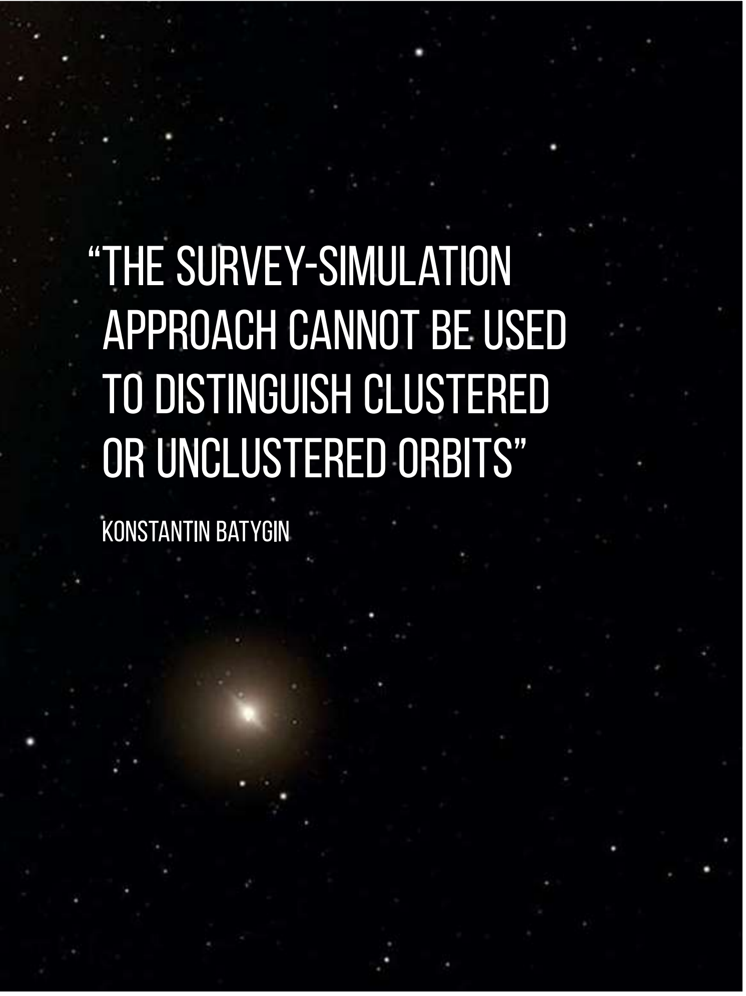
"But you cannot simply look at the data and draw robust conclusions because of this effect called observational bias. It takes into account factors such as where you pointed the telescope, when you took the observation and how faint of an object the telescope was able to see.

"Because the ETNOs are on exceptionally long, skinny orbits, they can only be seen for a very short segment, when they are closest to the Sun. This makes the observational biases present in their discovery rather severe. Until our study, nobody had performed a meta-analysis on all of the ETNOs discovered by surveys with calculable biases. It turns out that when you properly account for these observational biases, the population of ETNOs we observe is fully consistent with a uniform – rather than a clustered – underlying distribution."

In carrying out their research, Napier and his team decided to look at ETNOs that were not studied by Brown and Batygin. Those original six were discovered by surveys with unknown biases, "so we were unable to properly analyse them," explains Napier. "We wanted to test an independent sample because in a larger, better controlled sample, you would expect the significance of the clustering to either stay the same or to increase. We found the significance decreased."

Napier's team did include two of the original six objects after their main analysis, however, giving them a total of 16. "We still found that the observations were consistent with a uniform underlying distribution," he adds. But does that mean talk of a Planet Nine is off the table?

Causing some confusion about the conclusion is the title of Napier's academic paper, entitled: No Evidence for Orbital Clustering in the Extreme Trans-Neptunian Objects. It jars with the content of the work itself, and Batygin has not been slow



> "THE SURVEY-SIMULATION APPROACH CANNOT BE USED TO DISTINGUISH CLUSTERED OR UNCLUSTERED ORBITS"
>
> KONSTANTIN BATYGIN

© Caltech

to seize on this. "The Napier et al study does not actually draw the conclusion in the title," he tells us. "The work demonstrates that the survey-simulation approach cannot be used to distinguish between clustered or unclustered orbits, and this is not particularly surprising. Heavily biased surveys like the Outer Solar System Origins Survey or Dark Energy Survey are very hard to de-bias, and given the limited number of detections in each survey, the fact that survey-simulation cannot rule out any distribution is not perplexing."

Brown agrees wholeheartedly. "If you read the paper really carefully, then the correct statement from the Napier analysis would be something like: 'Our survey was very biased, and this could not detect clustering at the level previously detected.' It's a big leap that there is no clustering, and it's one they don't make in the paper, but do in interviews. In fact, if we add their new objects to our full dataset instead of using their much more limited dataset, the clustering actually improves."

In our interview, Napier admits that the work doesn't rule out the existence of Planet Nine, saying only that it has "certainly weakened the case for it". He says he would have preferred the conclusion to have backed the original hypothesis. "It would have been more exciting if our findings showed strong evidence for clustering in the ETNOs, and thus for Planet Nine," he says.

"That being said, we still find our results exciting," he adds. "Even if it turns out that Planet Nine doesn't exist, there must be some explanation

# ORBITS IN THE OUTER SOLAR SYSTEM

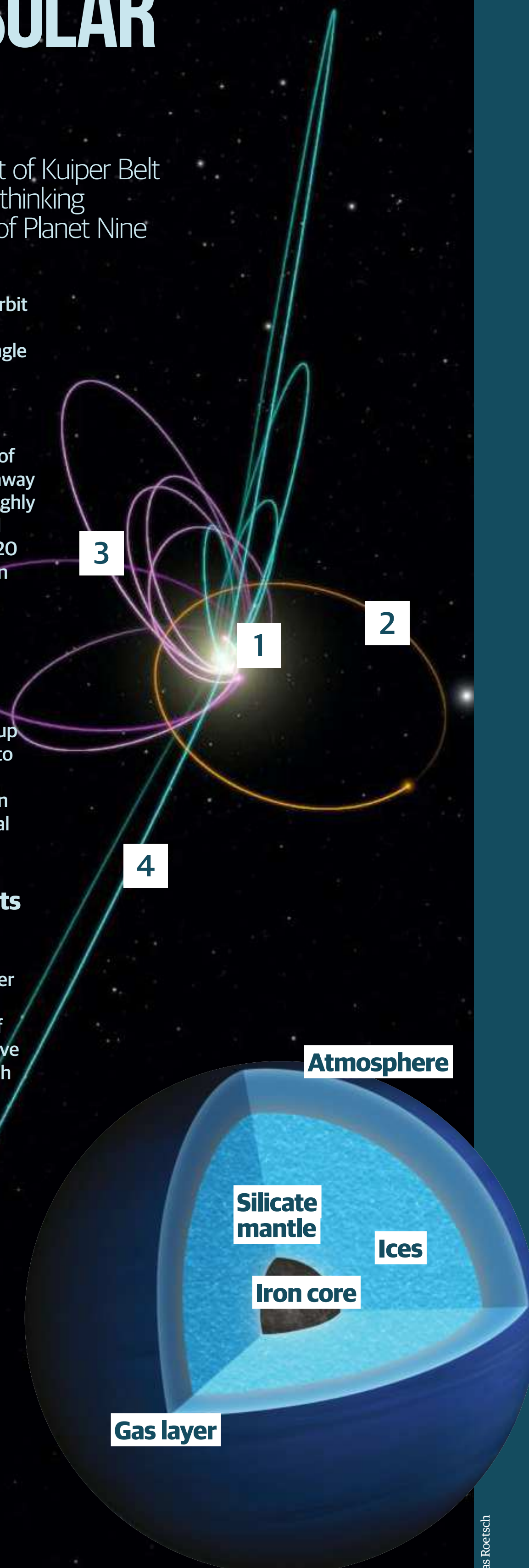
The behaviour of a set of Kuiper Belt Objects is fuelling the thinking behind the existence of Planet Nine

**1 Orbit of Neptune**
Here in the centre is the orbit of Neptune, which takes 165 Earth years to complete a single rotation around the Sun.

**2 Planet Nine's orbit**
As you can see, the orbit of Planet Nine is much farther away than Neptune. Indeed, the highly elongated orbit is far beyond Pluto, and it could be about 20 times farther from the Sun on average than Neptune.

**3 Effect on other objects**
Six distant trans-Neptunian objects have orbits that line up in a peculiar way. According to Brown and Batygin, only the gravity of a massive unknown planet exerting a gravitational pull can explain this.

**4 Perpendicular orbits**
Brown and Batygin's simulations predicted there would be objects in the Kuiper Belt with orbits inclined perpendicular to the plane of the planets. Observations have identified objects tracing such perpendicular lines.

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## FURTHERING THE CASE FOR PLANET NINE

American astronomer Mike Brown has worked on the hypothesis of another world for the last five years

**Some scientists have been unable to create a computer simulation that accounts for the clustered trans-Neptunian objects which form the basis of the theory of Planet Nine. Does this cast doubt over its existence in your mind?**
Many groups have reproduced computer simulations that make the Planet Nine cluster. The physics is well understood. It is neither difficult nor mysterious.

**Would you say the suggestion that you observed a small portion of the sky during a specific part of the year at a specific time of day is valid?**
I haven't heard that suggestion. Our survey is the only one that doesn't do that. The others are much more limited.

**How strong is the evidence for a Planet Nine in light of the recent study?**
The Napier paper neither adds nor subtracts to the Planet Nine hypothesis, though adding in the new objects would strengthen the hypothesis if we combined it with our full dataset – we haven't done this thoroughly yet, though. I would say the Planet Nine hypothesis is as strong as it used to be.

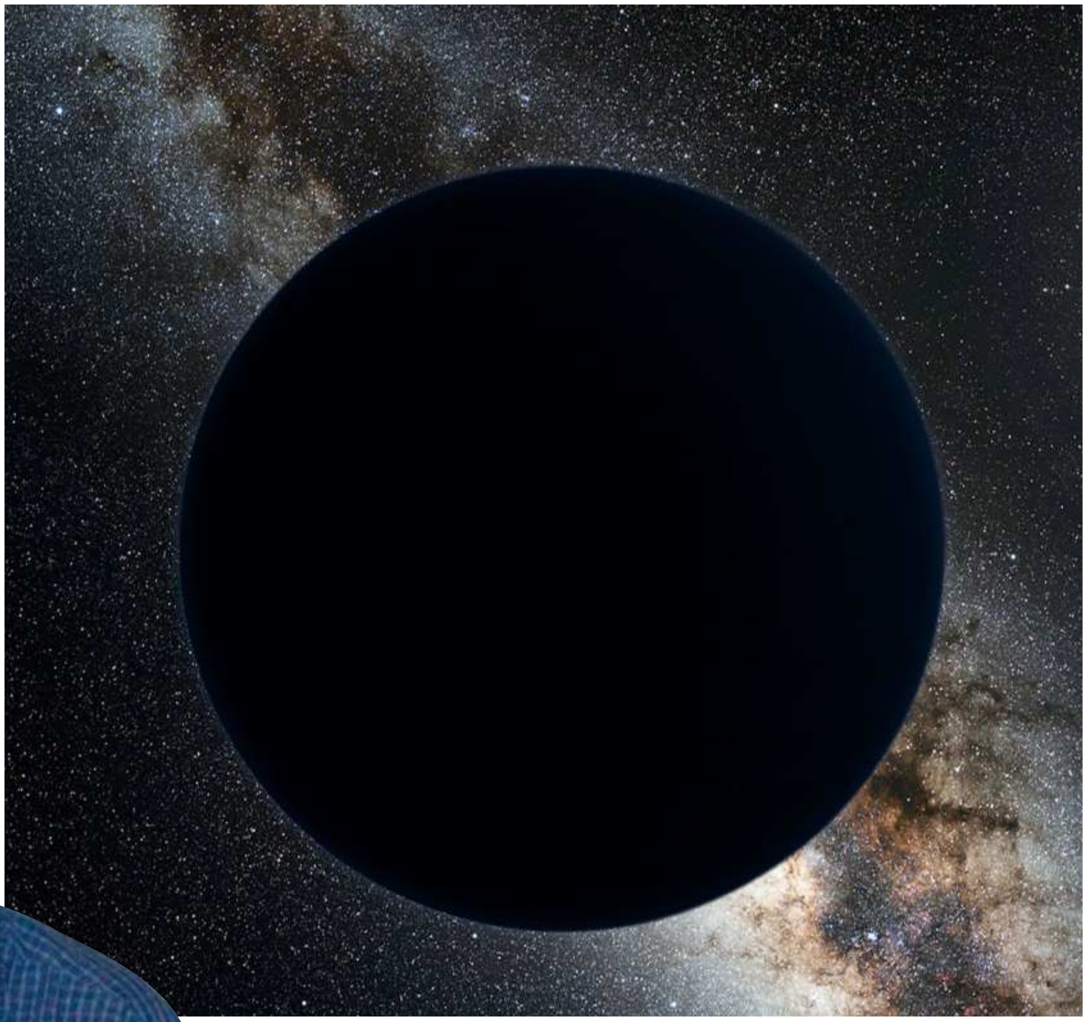
for the orbital behaviour of some of the strangest objects in our Solar System. Examples of such anomalies include Kuiper Belt Objects on highly inclined orbits and objects that never come closer to the Sun than twice the distance of Neptune. Mysteries like this are what keep us going."

As far as Batygin is concerned, the mystery surrounding Planet Nine is still in favour of it being out there somewhere. He says it has been clear for a long time that individual surveys cannot overcome their own biases to rigorously determine clustering one way or another. "In fact, this has already been pointed out multiple times, and the Napier et al analysis combines the well-characterised surveys, but still finds the same answer," he says. "For this reason, in order to determine the 'false-alarm probability' of the clustering, it makes sense to instead do an observability analysis which takes advantage of the full dataset to determine statistical significance." Batygin says he did exactly this in a paper with Brown published in 2019: "The analysis demonstrates that the chances that the data are not clustered is only 0.2 per cent."

By this, Batygin is theorising that the chance of clustering happening naturally without any gravitational pull from a body such as Planet Nine is extremely slim. What's more, as well as the clustering of orbits, the ETNOs with perihelia beyond 50 AU are too sufficiently distanced from Neptune to experience significant gravitational perturbations from it, so it points to something having an effect.

"An important point to understand is that the Planet Nine hypothesis is not just one thing," Batygin says. "There is a collection of lines of evidence that all paint the same picture: clustering of the apsidal lines, grouping of the angular momentum vectors, detached perihelia of long-period Kuiper Belt Objects, excitation of distant Kuiper Belt Objects to high inclinations and generation of the retrograde centaur population of the outer Solar System. The fact Planet Nine ties all these outer Solar System anomalies together gives me some confidence that we are on the right track."

In that sense, he doesn't perceive the study by Napier to have much of an effect on the original hypothesis. "There is one more very important point to understand, which routinely gets lost in translation," he continues. "The distant Kuiper Belt is made up of stable as well as unstable objects, and



**Right:** An artist's impression of Planet Nine with the Sun in the very far distance, circled by the orbit of Neptune

**Below:** Brown bears the nickname of 'Pluto killer'

in the Planet Nine story, it doesn't matter what the unstable objects do.

"If you look at the data, the stable, high-perihelion objects cluster very well, while the unstable objects are all over the place. That's what the theoretical model predicts too. You can imagine a whole range of observational biases that can cause clustering, but it's impossible to bias based on dynamical stability. Because the Napier et al dataset is roughly half stable, it's not a huge surprise they cannot prove that it's clustered." But does that still mean it has to be a planet causing the clustering? With the theory suggesting that gravity is at play, planets are not the only objects able to exert a gravitational pull. Dark matter or a primordial black hole are among the alternative suggestions.

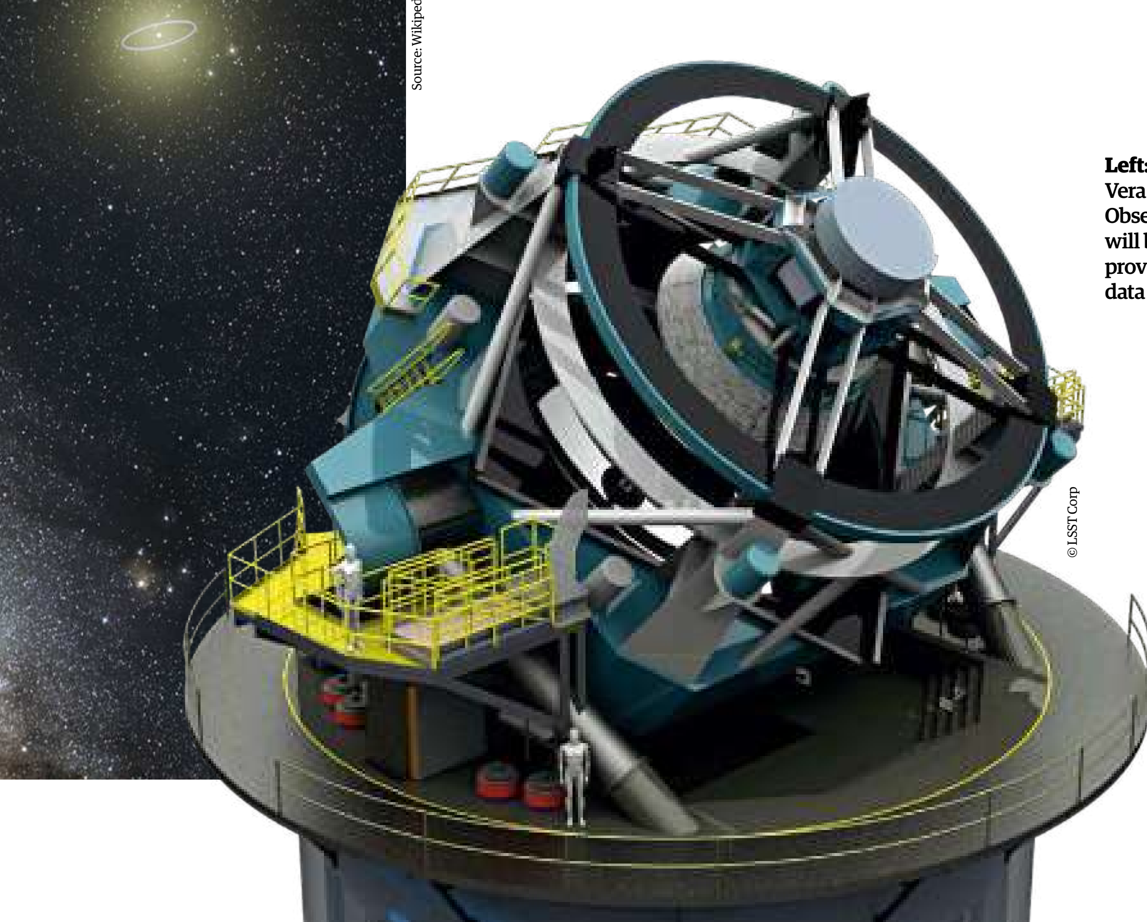
Napier reckons a planet would be the most likely explanation, so long as it's one day proved that the clustering is persistent. "It's hard to imagine it being caused by a dynamical mechanism other than Planet Nine if the clustering is persistent and not transient," he says. But recent work has shown that it's possible we are observing a temporary clustering of the ETNOs. It's clear more work needs to be done.

Certainly, the hypothesis of a Planet Nine is not going away any time soon. "I'm still quite optimistic that Planet Nine exists," says Batygin, with the use of the word 'quite' being notable. Napier, on the other hand, concludes: "I'm hopeful, but not optimistic. It might be there; it might not." Its existence would make life easier, but only one thing would really nail it. "Direct detection would be best," says Batygin, "and the answer to anything short of that is basically more data."

Napier agrees, and both are pinning their hopes on the Vera C. Rubin Observatory in Chile, which is coming online soon. The Legacy Survey of Space and Time at the observatory means the census of trans-Neptunian objects will expand substantially. One of the reasons why sufficient data has been hard to come by so far is access to telescopes and a focus on ETNOs in particular. Estimates are that the survey will discover more ETNOs, and with that data we'll be able to make a compelling statement.

One thing's for sure, there's a willingness for a discovery. In truth, most scientists would love to actually find Planet Nine. "A new planet would be extremely cool, and it would solve a lot of anomalies that we don't understand about our Solar System," Napier says. "But we have to entertain the possibility that there is no Planet Nine and continue searching for alternate explanations of those anomalies." We can only wait with bated breath.

**David Crookes**
*Science and technology journalist*
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.



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**Left:** The Vera C. Rubin Observatory will be able to provide new data on ETNOs

## THE THEORIES

What could be affecting the extreme trans-Neptunian objects?

### 1 Planet Nine

Modelling in 2016 by Brown and Batygin at Caltech hypothesised that six ETNOs had similar orbits because a large planet well beyond Neptune was exerting a massive gravitational pull on them. The scientists are sticking to this theory, and 19 ETNOs are now shown to exhibit a similar tilt and eccentric orbital pattern. This theory has yet to be proved or disproved.

© Getty

### 2 There's no clustering

According to a recent study headed by Napier, it is possible that there is no clustering in the first place. Other work suggests that any clustering could be temporary, and if either of these are the case then the likelihood of any gravitational pull being exerted is ruled out, thereby leaving any case for a Planet Nine severely dented.

© NASA

### 3 Something else is at play

If the ETNOs are indeed being affected by something in the Solar System, does it have to be a planet? Some scientists are looking into the possibility of a primordial black hole – a black hole which formed soon after the Big Bang – but these are still hypothetical. Dark matter is another potential theory, but again it's one hypothetical explaining another.

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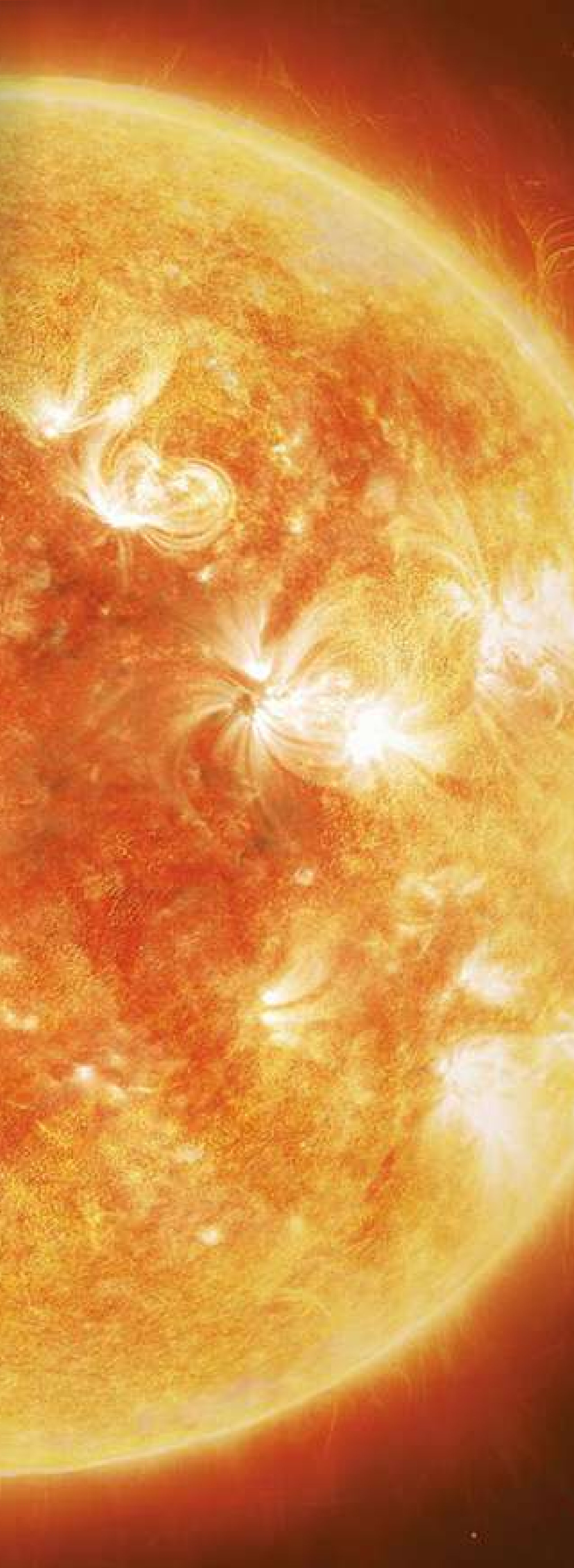
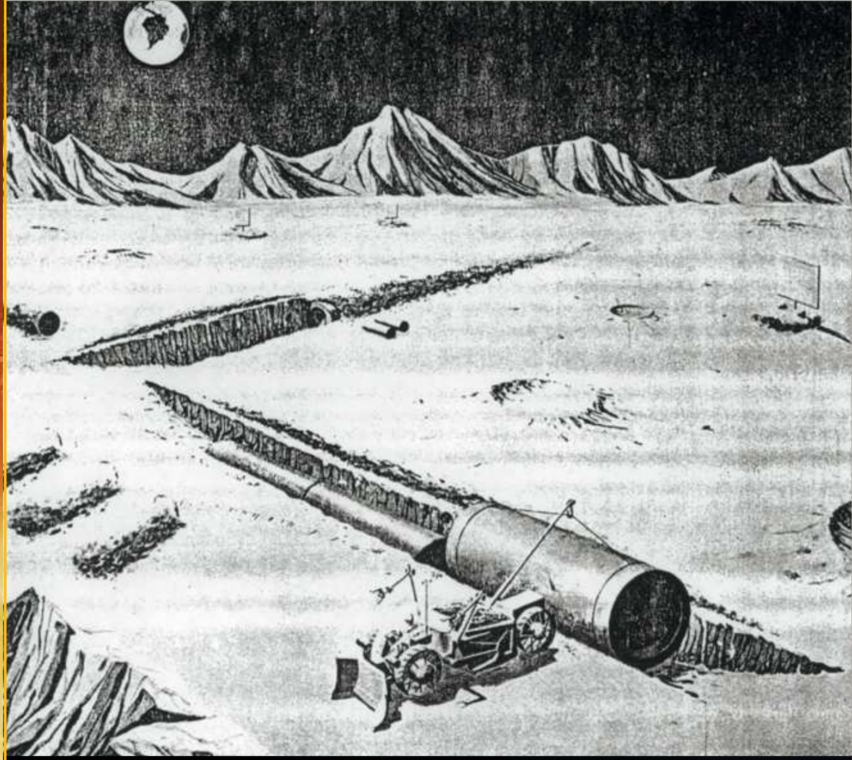
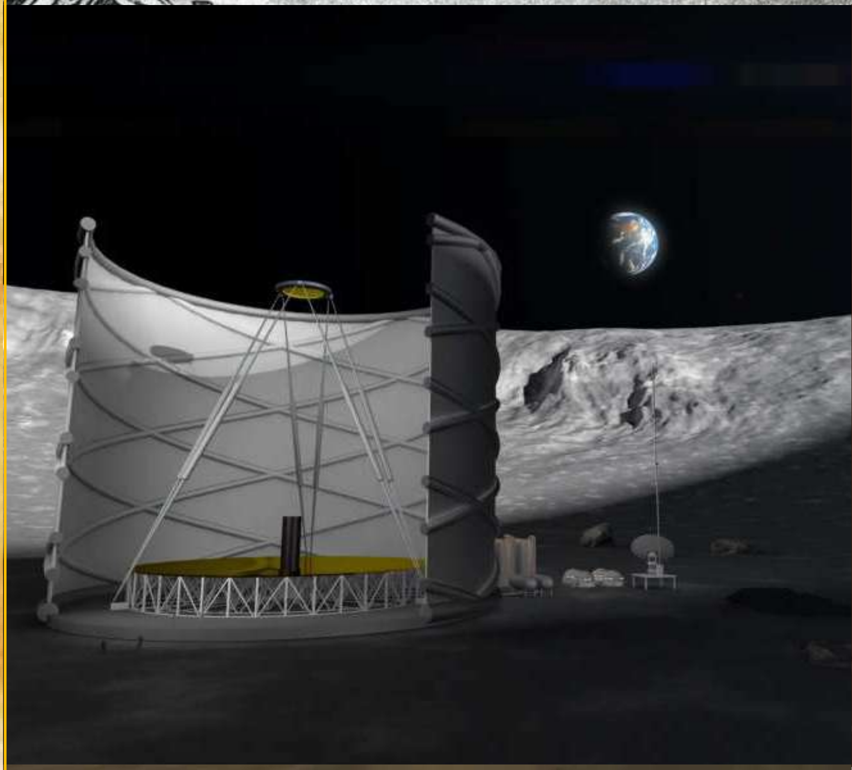
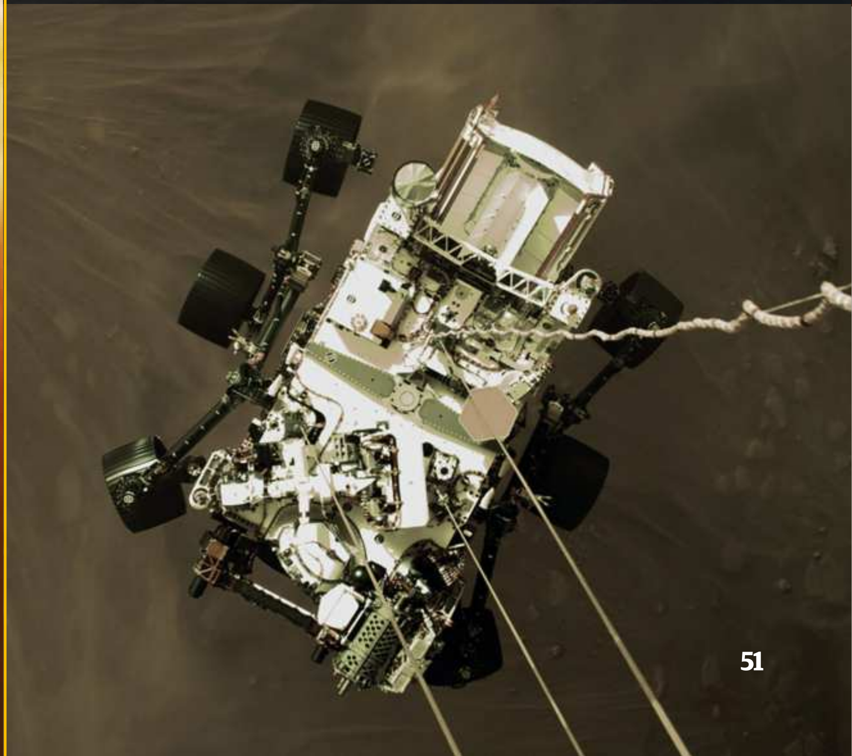
# Exploration

## Discover how humankind is blasting off into space



"This decade promises to reveal even more about alien worlds"

# ULTIMATELY LARGE TELESCOPE ON THE MOON

## With a big enough telescope, we could look back to the first stars – and from another world

As we look up into the night sky, one of the most counterintuitive aspects for the general observer is that they are looking back in time. As Douglas Adams said: "Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist, but that's just peanuts compared to space." With the speed of light in a vacuum fixed at 300,000 kilometres (186,411 miles) per second, it governs how long it takes for the light we see to travel from celestial objects. A second from the Moon, eight minutes from the Sun, 4.3 years from the nearest star and so on, meaning the stars we see in the sky are as they were years ago.

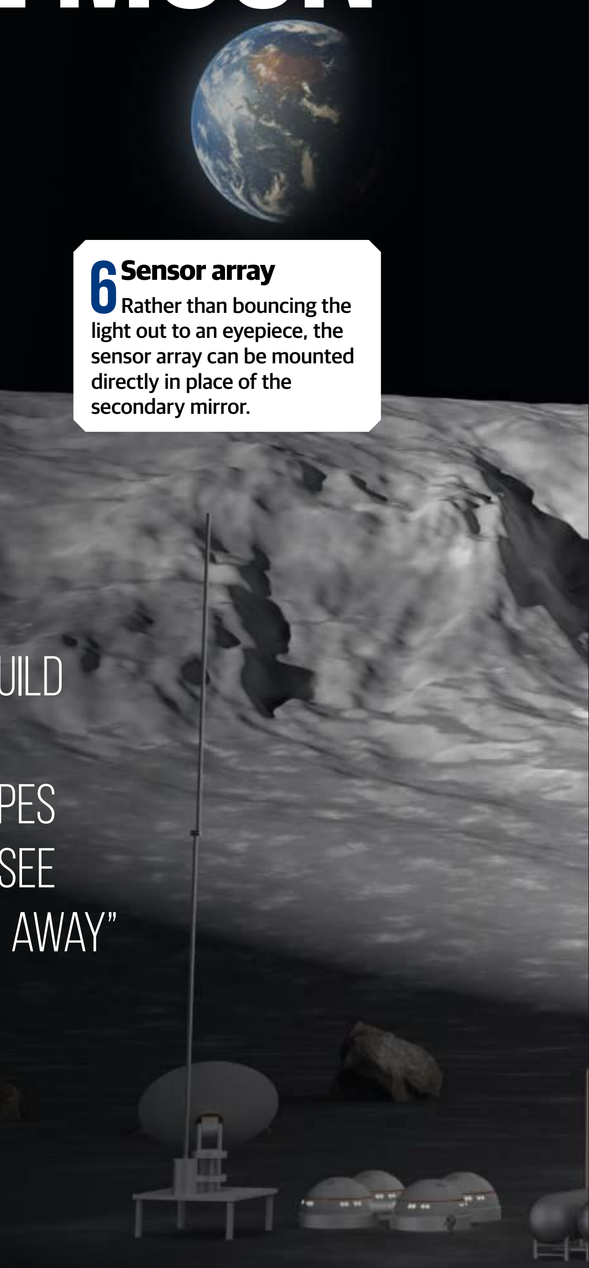
This almost time travel-like effect means that as we build larger telescopes we can see further away, and therefore further back in time. Light from a given source gets rapidly spread out as it expands in all directions as a sphere. In principle, if we have a sufficiently large telescope with a large enough light-gathering capacity, we could see far enough to see back to the first stars. Hubble, over its tremendous 30-year career, has enabled us to push towards this. Its successor, the much delayed James Webb Space Telescope, has a mirror that can collect six times more light and should let us image the very first galaxies. But a team of astronomers at the University of Texas at Austin, led by NASA Hubble Fellow Dr Anna Schauer, have proposed that an old NASA concept for a large lunar-based telescope would be large enough to see the first stars, which formed before galaxies.

Ground-based observatories can produce tremendous results, but will always be peering through the atmosphere – thus the move towards orbiting telescopes – but being in free orbit brings its own challenges, especially as the size of structures grows. So the team are looking to combine the best aspects of both, and build a telescope on the Moon. If built, the Ultimately Large Telescope would be based in a crater in the lunar polar regions, and could be as much as 100 metres (328 feet) across, over 1,700 times the collecting area of Hubble. While not being steerable, it would stare deeply into one region of space, collecting huge quantities of light and data. However, producing and transporting such a large astronomical reflecting surface to the Moon presents significant challenges. The study group has proposed an interesting way around this: a liquid mirror.

If a circular tray of liquid is spun, the liquid is partly flung out towards the edge, dipping down in the middle, and the surface forms a parabolic dish. The big advantage of liquid mirrors is cost saving in manufacturing. The largest yet built was the six-metre (20-foot) Large Zenith Telescope (LZT) operated by the University of British Columbia, the mirror of which was calculated to be one per cent the cost of a glass mirror the same size.

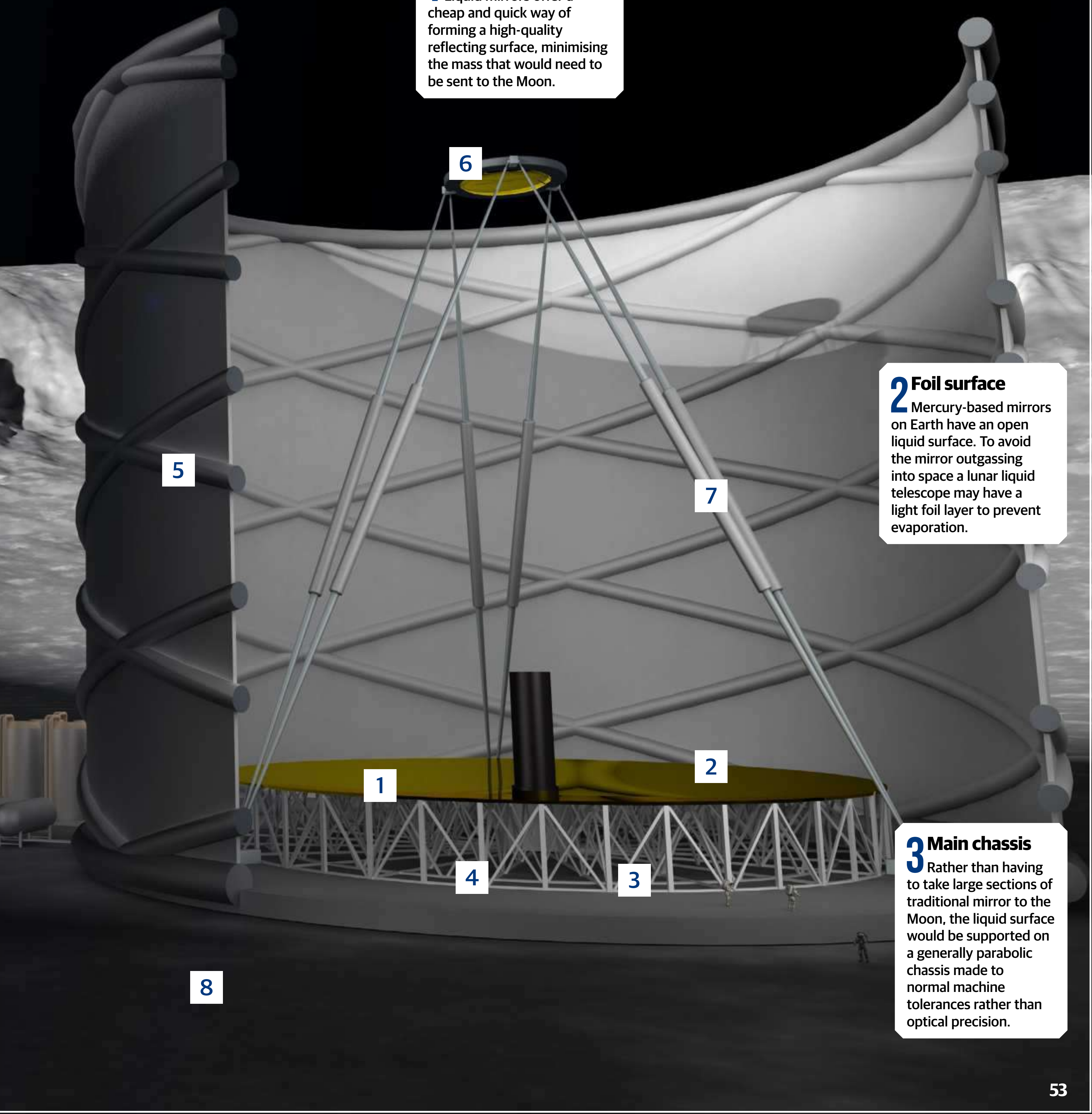
"AS WE BUILD LARGER TELESCOPES WE CAN SEE FURTHER AWAY"

The LZT used a thin layer of mercury on a generally parabolic carrier. A prospective Moon-based telescope couldn't use liquids in the vacuum of space, so may feature a thin foil layer that is supported and shaped by the liquid underneath. While it may be some time before we see such a facility constructed, the project has been nicknamed the Ultimately Large Telescope. If it comes to fruition, the lunar observatory may be able to show us the very first light of the universe.



**6 Sensor array**
Rather than bouncing the light out to an eyepiece, the sensor array can be mounted directly in place of the secondary mirror.

**8 Lunar poles**
Liquid telescopes can only look up. At the equator they will scan the sky. Placed at the poles the ULT will be able to stare deeply into one region, reaching out for the first stars.




### 4 Rotational bearings
Comparatively light as the system is, the 100-metre (328-foot) aperture will need some significant bearings to enable it to make a few revolutions per minute.

### 5 Sun shade
Shown in the project illustrations with helical ribs, this will likely be a collapsible structure of some sort. Once installed it will shield the system from extraneous light.

### 7 Telescopic supports
In the project illustrations the sensor array is supported by telescoping struts. All aspects of the engineering design will focus on minimising launch mass and volume.

### 1 Liquid mirror
Liquid mirrors offer a cheap and quick way of forming a high-quality reflecting surface, minimising the mass that would need to be sent to the Moon.

### 2 Foil surface
Mercury-based mirrors on Earth have an open liquid surface. To avoid the mirror outgassing into space a lunar liquid telescope may have a light foil layer to prevent evaporation.

### 3 Main chassis
Rather than having to take large sections of traditional mirror to the Moon, the liquid surface would be supported on a generally parabolic chassis made to normal machine tolerances rather than optical precision.

© Adrian Mann

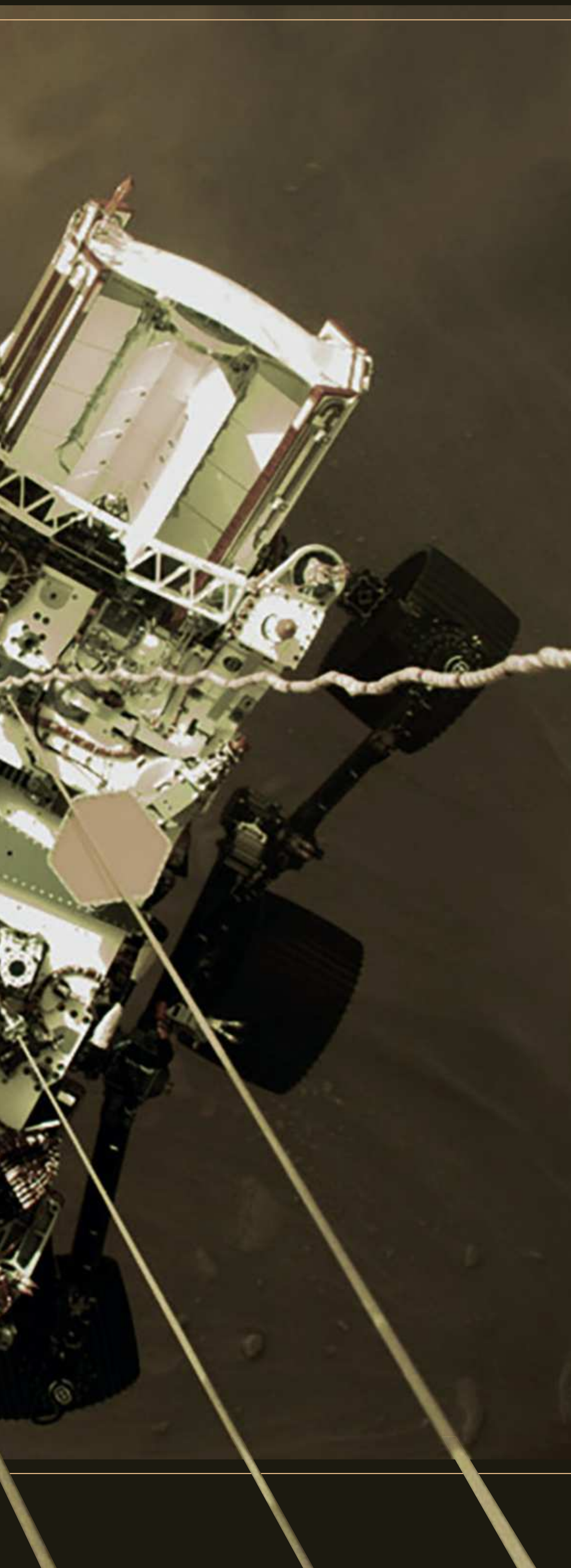
# PERSEVERANCE ON MARS

## NASA'S LATEST MARTIAN ROVER HAS BEGUN ITS EPIC QUEST TO FIND EVIDENCE FOR PAST LIFE RESIDING IN JEZERO CRATER

Reported by Stuart Atkinson

Perseverance might not be the first rover to land on Mars – a small plaque mounted on it shows it is the youngest member of a 'family tree' of Red Planet rovers – but it is certainly the most capable so far. Almost groaning under the weight of cameras and scientific instruments, nuclear-powered Perseverance set down safely on Mars in a cloud of billowing orange dust on 18 February, and since then has begun to explore Jezero crater.

Perseverance's mission is simple and exciting: it's on a quest to look for evidence that Mars once had life. It will do that by studying rocks and material inside the crater, specifically within the layers of ancient sediment that form a striking, fan-shaped delta that pushes into the crater from the west. While it would be thrilling for the rover to spot a fossil sticking out of the rock, it's much more likely that any evidence it finds of past Martian life will take the form of chemical traces – blips on a chart. Perseverance will also collect samples of material from Jezero crater and leave them there for a future mission to collect and bring home for study using instruments that can't be taken to Mars. Perseverance is our best chance yet of answering one of the oldest, most exciting and tormenting questions in science: was there once life on Mars?



# TOUCHDOWN

Because Perseverance and the support hardware used to land it safely on Mars were fitted with more cameras than any previous mission, we have been treated to some truly unique images, including this one showing the rover actually touching down on the surface of the Red Planet. This high-resolution still image is part of a video taken by several cameras that whirred and clicked away as the rover landed in Jezero crater. A camera aboard the descent stage captured this shot, which shows Perseverance surrounded by a billowing cloud of dust as its wheels touched the surface for the very first time. Also visible is the tether connecting the rover to the descent stage.

**Left:** Perseverance touches down on Mars in a swirling cloud of dust

**Below:** The MRO's HiRISE camera photographed Perseverance and its parachute dropping towards the landing site in Jezero crater

# FALLING THROUGH THE MARTIAN SKY

In this immaculately timed image taken on 18 February 2021 by the High Resolution Imaging Science Experiment (HiRISE) camera aboard the Mars Reconnaissance Orbiter (MRO), the descent stage holding the Perseverance rover can be seen falling through the Martian atmosphere, with its parachute trailing behind. The image also shows the target of the Perseverance mission – an ancient river delta, entering Jezero crater from the left. Before Perseverance arrived, many professional and armchair scientists alike were hoping HiRISE would capture an image of it beneath its parachute, just as it photographed Curiosity's dramatic arrival a dozen years earlier. Taking this image required precise timing and a lot of clever flying by the MRO team.

WATCH NASA'S LIVE COVERAGE OF THE LANDING

AR SCAN HERE

## BLOWING AWAY THE DUST

The red colours and strange shapes visible in this striking image might make you think of something seen in the operating theatre of a hospital, but what it actually shows are streamers – whirls and curls of fine Martian dust being blown away from Perseverance's landing site as it was lowered down to the surface by its descent stage. It was taken by the camera mounted on the bottom of the rover.

## PERSEVERANCE'S PARACHUTE

Possibly one of the most striking images taken on landing day, this shows Perseverance's huge parachute lit from behind by the Sun. Hundreds of these images were taken, which were later combined to make a stunning video showing the parachute swaying and billowing in the wind. When this particular image was taken, the parachute was fully inflated, lowering the rover down gently to the surface. That pattern on the parachute isn't just a random collection of panels, however. It's a message, sneakily written in a special code, spelling out the Jet Propulsion Laboratory's motto: Dare mighty things.

## THE HEAT SHIELD FALLS AWAY

This remarkable image, taken by Perseverance's Lander Vision System Camera (LCAM), shows the rover's heat shield dropping away towards Mars after being released from the back shell during the spacecraft's descent through the Martian atmosphere. This was the first use of the system at Mars, which compared images from below the spacecraft to an onboard map, helping to guide the spacecraft to a safe landing spot in Jezero crater. Past missions had deemed Jezero crater too hazardous to be a landing site because of its cliffs, dunes and boulders, but using LCAM the rover was able to find and steer itself down to a safe landing site close to the preserved remains of an ancient river delta. Without LCAM, a landing in such a 'busy' area would have been impossible.

**Right:** Its job done, Perseverance's heat shield falls away

**Left:** Perseverance pictured on the ground, ready to begin roving across Mars

## SAFELY ON THE GROUND

The HiRISE camera aboard NASA's MRO didn't just take an amazing image of Perseverance falling towards Mars on the end of its parachute; it also took this stunning view of the rover after it had landed on the surface. Taken the day after landing, this image is a close up taken from a larger image showing several different parts of the Mars 2020 mission landing system that got the rover safely on the ground. The bright 'fans' on either side of the rover are areas where the exhausts of the descent stage's engines blew away the dark dust from the surface, exposing lighter rock and material underneath.

EXPLORE PERSEVERANCE'S LANDING SITE (NASA)

AR SCAN HERE

**Right:** With the covers off its cameras, Perseverance could finally see the beauty of Mars for the first time

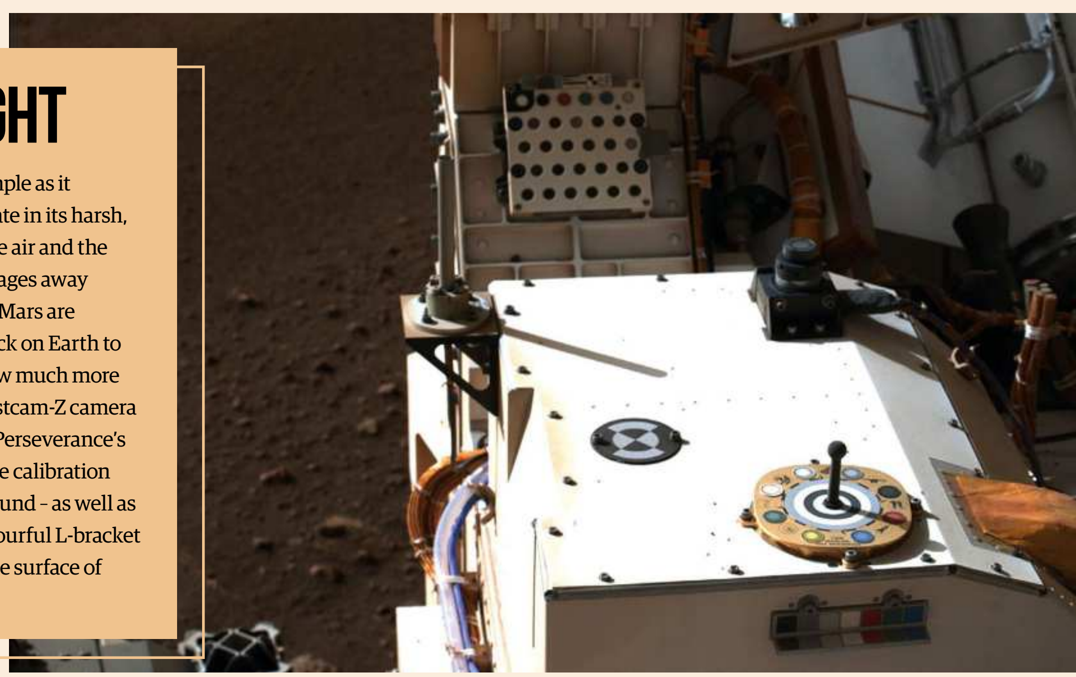
**Below:** Perseverance has several 'calibration targets' designed to help its science team balance the colour of the images taken by its suite of cameras

# PERSEVERANCE OPENS ITS EYES

Very shortly after landing – even before the cheers in Mission Control had died down – Perseverance sent back a handful of images taken by the hazard avoidance cameras (hazcams) on its underside. But because the cameras still had their protective caps on to prevent them being damaged by dust kicked up during the landing, those images were blurry and indistinct. But soon those caps were popped off, and then Perseverance began sending back images like this: the first high-resolution colour image to be sent back after its landing. Now the mission scientists got their first proper look at the landing site, seeing a typically Martian scene – a vast, open plain littered with rocks beneath an orange-pink sky.

# GET THE BALANCE RIGHT

Taking pictures on the surface of Mars isn't as simple as it sounds. Very special cameras are needed to operate in its harsh, frozen environment, and then things like the dust in the air and the weaker sunlight there combine to shift the colour of images away from those the naked eye would see. Spacecraft sent to Mars are fitted with 'calibration targets' which allow the team back on Earth to balance the colours of their images and recreate the view much more accurately. This image, taken by the mast-mounted Mastcam-Z camera on 20 February 2021, the second Martian day, or sol, of Perseverance's mission, shows Mastcam's primary-colour and grayscale calibration target – the colourful, circular object in the right foreground – as well as the camera's secondary calibration target, the small colourful L-bracket just below the primary target. On the left you can see the surface of Mars, covered with rocks and dust.



## FIRST DRIVE

Once a rover like Perseverance has landed safely on Mars, it can't just rev its engine and set off across the desert like it's starring in a Martian *Fast and Furious* film; its many systems have to be checked out thoroughly and patiently to ensure they weren't damaged during the descent and landing.

However, eventually it's time for the wheels to turn for the first time. On 4 March 2021, after weeks of preparation, Perseverance completed its first short drive. This image, taken by the rover's navigational cameras, shows the rover's first tracks on the dusty surface of Mars.


**Left:** Celebrations occurred as Perseverance left its first wheel tracks in the ruddy dust of Mars

## FIRST COLOUR PANORAMA

**This panoramic view, taken on 20 February by the navigational cameras, or navcams, aboard NASA's Perseverance rover, was stitched together from six individual images after they were sent back to Earth. It was the first time the mission scientists - and everyone following the mission around the world - realised how rocky and dangerous the terrain around the landing site was, appreciating just how successful Perseverance's landing system had been in finding somewhere safe for it to set down in Jezero crater.**

**Left:** Our first panoramic view of Perseverance's landing site

## A FASCINATING FUTURE DESTINATION?

When the first images came back from Perseverance, they showed this intriguing feature - a remnant of the delta, detached from the main body, which many scientists are very keen to examine with Perseverance's suite of instruments. This hill of crumbling rock is about 2.3 kilometres (1.4 miles) to the west of the Perseverance landing site and is about 200 metres (660 feet) across. The image has been colour-balanced to show approximately what the scene would look like if we viewed it with human eyes.

**Right:** This remnant of the river delta might be visited by Perseverance later in its mission

# MARS IN 'REAL COLOUR'

If you stood next to Perseverance on the floor of Jezero crater, what would you actually see? Would it look as red or as pink as it does in the photos? This image, taken on 5 March 2021 by one of the rover's navigational cameras, was colour-calibrated to show the approximate view an astronaut standing on Mars would enjoy. It shows the tracks left on the dusty surface from the rover's first drive and an area scoured by the descent stage's rockets – the lighter coloured area in the middle ground – as it gently lowered Perseverance to the surface.

**Below:** Mars as your eyes would see it if you were standing beside Perseverance

ALL ABOUT THE PERSEVERANCE ROVER AR SCAN HERE

# FORGOTTEN PLANS TO REACH THE MOON

**BEFORE APOLLO, MANY INGENIOUS LUNAR LANDING SCHEMES WERE PROPOSED THAT COULD HAVE CHANGED HISTORY**

Reported by Nigel Watson

Humanity has long fantasised about going to the Moon, but it was only in the 19th century that writers like Jules Verne and H. G. Wells began to think about using technology to make this dream a reality. The enthusiasm generated by such concepts, combined with the heating up of the Cold War, made the Moon a feasible target for exploration, propaganda and military exploitation. The outcome was several top-secret schemes developed by the US Air Force (USAF), US Army and independent privately funded contractors.

The USAF desired to be at the forefront of developing rocketry and spacecraft, feeling the urgent need to respond to the Soviet Union's launch of Sputnik 1 on 4 October 1957. In January 1958, USAF Brigadier General Homer A. Boushey gave a speech to the Aero Club in Washington, where he stated: "He who controls the Moon controls the Earth. Our planners must carefully evaluate this statement for, if true - and I for one think it is - then the US must control the Moon."

In February 1958 the newly formed Advanced Research Projects Agency (ARPA) chose the USAF to run the nation's space programs. Under the leadership of Harry Lee Evans, a comprehensive plan to conquer space was quickly put forward. Underlining the sense of urgency, the proposal was titled Man In Space Soonest (MISS). The hardware and flight capabilities of a simple one-person, cone-shaped capsule would be tested in six robotic flights, followed by six more missions using animals to test life-support systems. Once these tests were passed, manned flights would begin. They would check out guidance and control systems, re-entry techniques and would culminate in a parachute landing at sea.

The next phase would have been the Man In Space Sophisticated (MISSOPH) program. This had three stages. The first was robotic and animal testing of a capsule that could stay in space for two weeks - the time it would take to make a Moon trip. MISSOPH II would send a spacecraft to a distance of 64,374 kilometres (40,000 miles), and test how it would cope with a re-entry speed of 38,405 kilometres (23,864 miles) per hour, the speed a craft returning from the Moon would achieve. MISSOPH III would test a shuttle that would land back on Earth like an aircraft and was planned for lunar and Earth orbital missions.

Alongside the MISSOPH missions, starting in April 1960 the USAF would have run the Lunar Reconnaissance (LUREC) program using robotic craft. LUREC I would test tracking and communications with a spacecraft 402,336 kilometres (250,000 miles) away, while LUREC II would test the guidance systems to ensure they could accurately land a craft at a specific place on the Moon. These craft would capture TV images and gather scientific information about the Moon to enable planners to select suitable landing sites. Then LUREC III, using retrograde rockets to land on the Moon, would send back further data.

It was only after those phases that Project LUMAN would come into play in May 1962. LUMAN I would send animal flights around the Moon to test the hardware and systems before LUMAN II sent astronauts on a circumlunar flight. LUMAN III would send robot craft to land a payload on the Moon, and LUMAN IV would land on the Moon and return to Earth.

It was with LUMAN V, planned for 1965, that a single astronaut would ride a 'Big B' rocket to make the momentous journey to the lunar surface and

"IT TOOK A VERY SPECIAL SET OF CIRCUMSTANCES TO MOTIVATE SPENDING BILLIONS ON A LANDING PROGRAM" MICHAEL NEUFELD

## THE SCRAPPED PROJECTS

The US Air Force, Army and private contractors produced these major studies before NASA took charge

### PROJECT LUMAN

- Overseen by Colonel Harry Lee Evans
- Report delivered on 25 April 1958
- Proposed a series of robotic and animal flights of a simple MISS capsule
- Testing of larger MISSOPH capsule
- MISSOPH III, a lifting-body craft for lunar and Earth orbital missions
- Lunar Reconnaissance (LUREC) robotic craft would prepare the way for LUMAN missions
- Human circumlunar flights
- Human trip to the Moon

### PROJECT MALLAR

- Pioneered the lunar orbit rendezvous (LOR) concept
- Proposed using different mission modules
- Would require a space station, entry vehicle and assembly vehicle to prepare the mission for the lunar astronauts.
- Would take three to six days to go to the Moon
- Astronauts would spend 24 hours on the Moon
- Another three to six days to return home

### PROJECT HORIZON

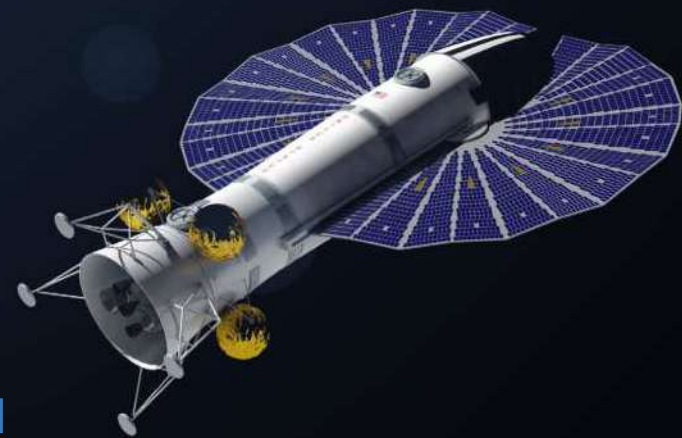
- The main intention was to create a lunar military base
- Proposed assembling spacecraft in low-Earth orbit
- Involved 40 Saturn V rocket launches before cargo delivery to the Moon
- Target was to land two astronauts on the Moon in 1965
- A permanent 12-person outpost would be operated from late 1966

### PROJECT LUNEX

- A direct flight to the Moon
- Would require a huge three-stage rocket booster
- Would carry three astronauts using a shuttle-type spacecraft
- A target date of a 1967 Moon landing

# FORGOTTEN CRAFT

Inside the proposals that Apollo beat to the punch



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## PROJECT LUNEX

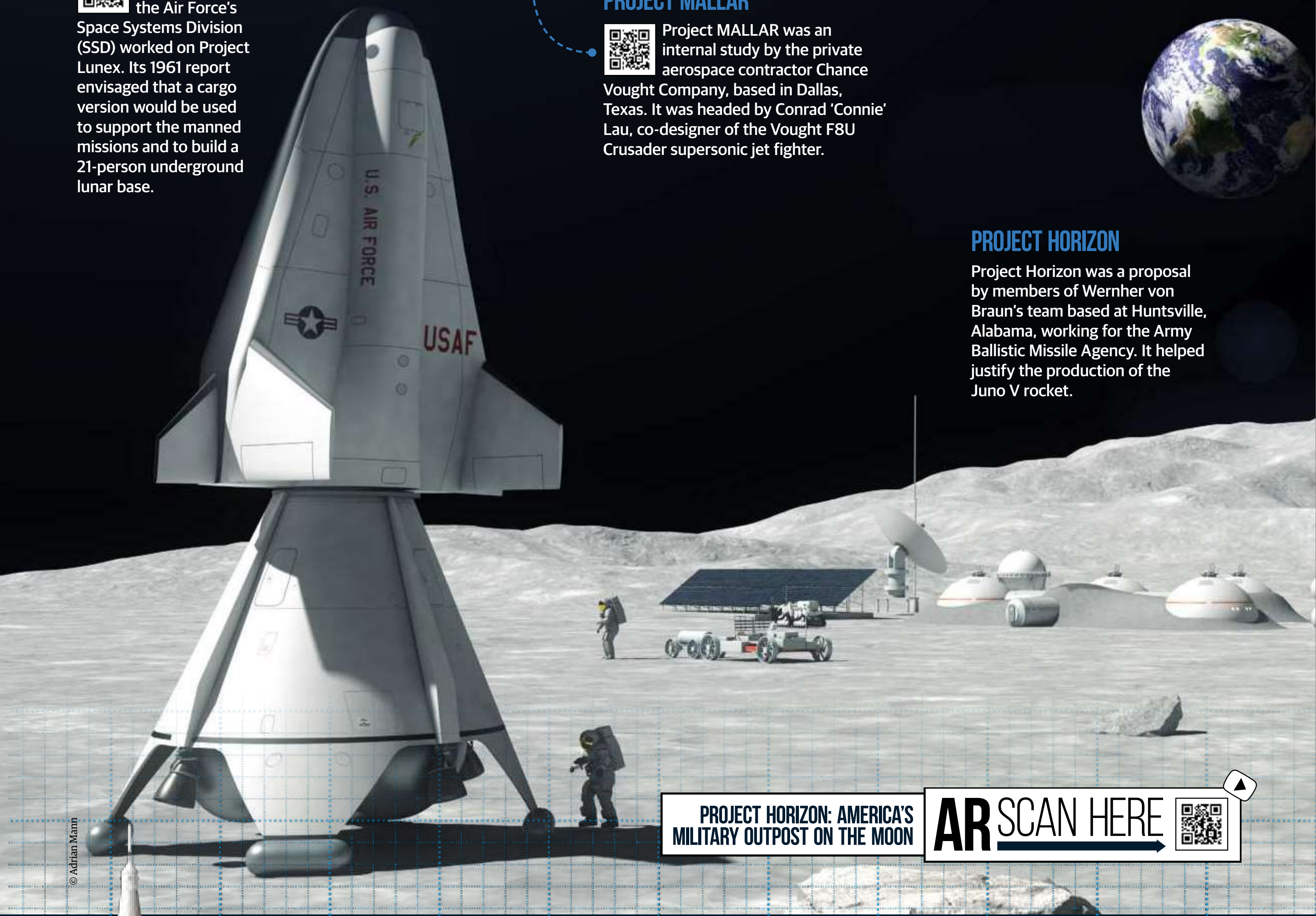
Having Project LUMAN rejected, the Air Force's Space Systems Division (SSD) worked on Project Lunex. Its 1961 report envisaged that a cargo version would be used to support the manned missions and to build a 21-person underground lunar base.

## PROJECT MALLAR

Project MALLAR was an internal study by the private aerospace contractor Chance Vought Company, based in Dallas, Texas. It was headed by Conrad 'Connie' Lau, co-designer of the Vought F8U Crusader supersonic jet fighter.

## PROJECT HORIZON

Project Horizon was a proposal by members of Wernher von Braun's team based at Huntsville, Alabama, working for the Army Ballistic Missile Agency. It helped justify the production of the Juno V rocket.

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PROJECT HORIZON: AMERICA'S MILITARY OUTPOST ON THE MOON

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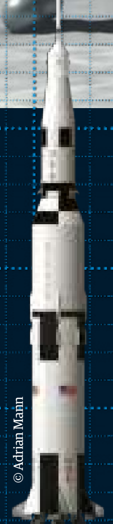

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# THE PATHWAY TO APOLLO

Numerous manned and unmanned missions made way for the program

### 4 OCTOBER 1957

The Soviet Union launched the first artificial satellite, triggering what became the Space Race between the US and the Soviets.

### 12 APRIL 1961

Yuri Gagarin became the first man to travel into space. He made one orbit of Earth during the 108-minute mission.

### 25 MAY 1961

Having suffered humiliation at the Soviet Union's dominance of spaceflight, Kennedy announced his goal of landing a man on the Moon by the end of the decade.

### 1961-1963

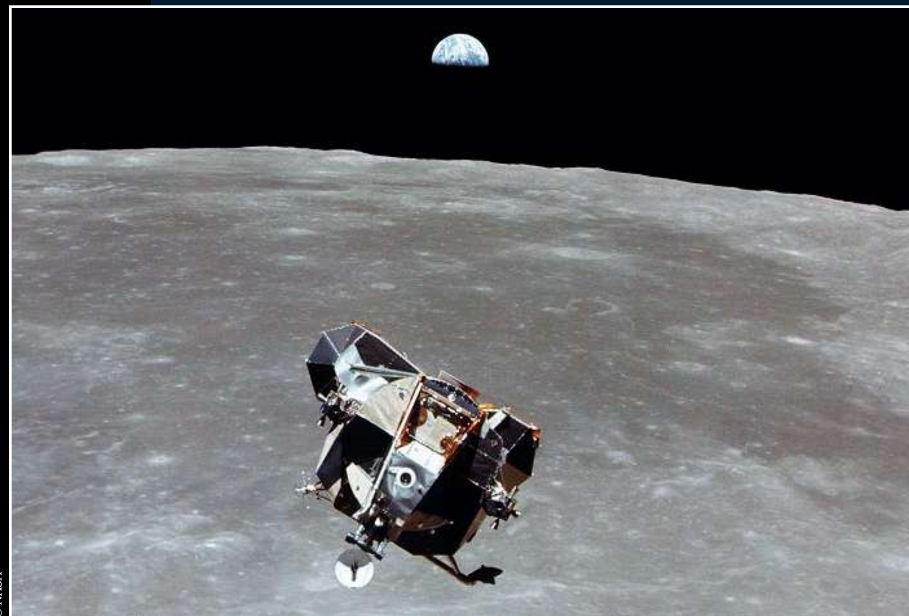
On 20 February 1962, John Glenn became the first US astronaut to orbit Earth in the one-man Mercury capsule. The six manned Mercury flights established a foothold for NASA.

### 1961-1965

Of the nine Ranger robot craft, three were deliberately crashed into the Moon to collect more than 17,000 images of the lunar surface.

### PROJECT LUMAN

Part of an ambitious Air Force plan by a team of about 60 people, it outlined a series of Man in Space Soonest (MISS) missions aimed at achieving a manned lunar landing and return.

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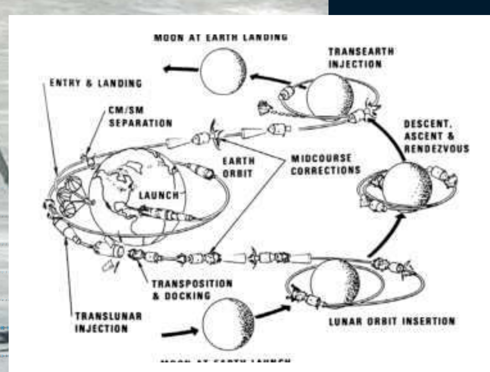
**Above:** The Lunar Module, with Earth behind, approaches the Apollo 11 Command Module after its successful Moon landing




© NASA

**Above:** Diagram showing the stages of the Apollo Moon missions, which used the LOR technique

back. The report was met with little enthusiasm, and was criticised for being too grand. It was felt that the USAF should rule out any interest in lunar missions and that any of its space projects should have a military requirement.

In December 1958, the aerospace contractor Chance Vought's astronautics division, under the direction of Thomas Dolan, put together a team to study vehicle concepts that could follow NASA's Mercury program. It quickly put an emphasis on possible lunar missions, and Conrad 'Connie' Lau was put in charge of Project MALLAR (MAnned Lunar Landing And Return).

The beauty of this scheme was that it involved using modular components and the use of rendezvous and docking techniques. It featured a two or three-person entry vehicle module that for Earth orbital missions would be attached to a payload module that could act as a space station for 14 days. For a lunar landing mission the modules for it would be assembled in Earth orbit and feature a two-person entry vehicle, a lunar mission module, a lunar landing module and a rocket stage to send it to the Moon. In lunar orbit the two-astronaut crew would transfer to the lunar landing module and descend to the Moon.

After 24 hours they would return to the orbiting modules, jettison the ascent stage of the lunar lander and return to Earth. The lunar mission module would be left in Earth orbit if desired, and the astronauts would use the remaining entry vehicle to get home. To provide electrical power it had a circular solar array that fanned out from the craft after launch, and it had spherical propulsion tanks attached to the outside of the craft.

The most important aspect of the design was that by using a lunar orbit rendezvous (LOR) technique, rather than sending a craft directly

**1965-1966**
Using a two-man capsule, Gemini was used for long-duration missions and to perfect rendezvous and docking manoeuvres necessary for the Apollo program.

**3 JUNE 1965**
Ed White became the first US astronaut to walk in space during the second manned Gemini mission.

**1966-1967**
A total of five Lunar Orbiter robot craft were sent to orbit the Moon to photograph it in even more detail. They also captured images of the far side to create an atlas of its whole surface.

**1966-1968**
Five Project Surveyor craft soft landed on the Moon to test the stability of the lunar surface, taking more than 87,000 images.

**1968-1972**
Conducted 11 manned missions. Apollo 7, 8, 9 and 10 tested the flight systems. Apollo 11, 12, 14, 15, 16 and 17 successfully landed and returned men to and from the Moon.

to the Moon, it would save 50 per cent of the total mission weight. At NASA, an LOR seemed too complex and dangerous, but John Houbolt, an engineer at Langley Research Center, worked hard at promoting the concept, and his MALLIR (MAnned Lunar Landing Involving Rendezvous) proposal was adopted for the Apollo program. Dolan failed to get any support from NASA for MALLAR, and further failures to attract any contracts involving Apollo led to his group fading from involvement in Moon landing missions.

Like the USAF's Project LUMAN, Wernher von Braun's team at the Army Ballistic Missile Agency saw the need to gain the military high ground by establishing a base on the Moon, which in addition could be used for scientific studies of the Moon and advancing further exploration of space.

Von Braun and his team thought that producing a large enough rocket booster for a direct Moon landing was impractical. He instead advocated for using a technique known as Earth orbit rendezvous (EOR). His Juno V - later renamed Saturn V - rockets would assemble a lunar rocket stage in Earth orbit that would rendezvous with a manned spacecraft. The manned craft would then be fired to the Moon by the rocket stage, and would slow down for a lunar landing when approaching the Moon. As early as 1952 he had put forward an ambitious plan to use EOR techniques to assemble three huge 3,964-tonne spacecraft that would take 50 astronauts to the Moon.

Less grandiose proposals for the base were detailed by von Braun's colleagues, Frank Williams and Heinz Koelle, in their 'Project Horizon' report submitted in June 1959. The report hedged its bets by proposing that a cargo of 2,721 kilograms could be soft landed on the Moon by the direct method, while crewed missions would be assembled in Earth orbit in conjunction with a space station.

Throughout 1964, 40 Saturn I and improved Saturn II boosters would prepare the way for a two-person Moon landing in April 1965. The building of the base would begin in earnest, with the delivery of 220 tonnes of cargo to the Moon by nearly 150 Saturn rockets. It was hoped that by November 1966 the base would be ready for a permanent 12-person task force. From December 1966 through 1967, a further 120 tonnes of cargo would be delivered to the base by 64 Saturn V launches. It was predicted that by the end of 1967, 42 astronauts would have been to the Moon and 26 would have returned after doing their stint of duty at the base.

The base would consist of living quarters, a science laboratory, medical and communications facilities and storage rooms inside metal cylinders linked together and arranged in an L-shape. They would be buried beneath the surface and covered by lunar material to protect the occupants from radiation, meteoroids and the hostile lunar environment. Power would be provided by two nuclear reactors buried underground at a distance from the main base.

A surface construction vehicle would be used to dig the channels and position the metal living units into place, while another lunar rover would be used for cargo carrying and exploration. The base would be protected against intruders by handheld claymore mines and nuclear-tipped rockets. With the formation of the National

"THIS NATION SHOULD COMMIT ITSELF TO ACHIEVING THE GOAL, BEFORE THIS DECADE IS OUT, OF LANDING A MAN ON THE MOON" PRESIDENT KENNEDY

WHAT HAPPENED ON THE MOON BEFORE APOLLO?

AR SCAN HERE

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**Left:** Apollo would be the program selected

**Below:** The large open-wheeled construction vehicle, with a digger, crane and robot arm, imagined for building the Project Horizon Moon base

# PROJECT APOLLO: HOW WE LAUNCHED TO THE MOON

**1 LAUNCH ESCAPE SYSTEM**
Used in an emergency to blast the Command Module away from danger during launch.

**2 COMMAND MODULE**
Three astronauts controlled the spacecraft, living inside this module for most of the mission.

**3 SERVICE MODULE**
Carried life-support systems for the crew and a rocket engine to fire it into and out of lunar orbit.

**4 LUNAR MODULE**
Stowed above Saturn V's third stage, this vehicle had a two-person crew section and a lunar landing stage. It was protected by an aluminium cone.

**5 THIRD STAGE**
One J-2 engine boosted the speed to achieve escape velocity, putting Apollo into Earth orbit. It was able to reignite to boost the craft to the Moon.

**6 SECOND STAGE**
In six minutes the five J-2 engines accelerated Saturn's speed to over 24,140 kilometres (15,000 miles) per hour.

**7 FIRST STAGE**
The rocket achieved a speed of around 9,656 kilometres (6,000 miles) per hour in just 2.5 minutes.

**8 F-1 ENGINES**
Five F-1 engines gave an incredible combined thrust of 7.5 million pounds (3.4 million kilograms).



| APOLLO 11 | APOLLO 12 | APOLLO 14 | APOLLO 15 | APOLLO 16 | APOLLO 17 |
|---|---|---|---|---|---|
| Neil Armstrong and Buzz Aldrin landed in the Sea of Tranquillity on 20 July 1969. Armstrong was the first to take one 'small step' on the Moon. | On 19 November 1969, Pete Conrad and Alan Bean landed in the Ocean of Storms. | Alan Shepard and Ed Mitchell landed in the Fra Mauro formation on 5 February 1971. | Landed near Hadley Rille on 30 July 1971. Astronauts Dave Scott and Jim Irwin were the first to use the lunar rover. | John Young and Charlie Duke landed in the Cayley Formation of the lunar highlands on 21 April 1972. | The last mission, crewed by Gene Cernan and Harrison Schmitt, landed in the Taurus-Littrow valley on 11 December 1972. |

Aeronautics and Space Administration (NASA) in 1958, such projects were put under its leadership, and Project Horizon faded into history.

President Kennedy announced to Congress on 25 May 1961: "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth." The USAF optimistically put forward another Moon landing plan: the Lunex Project.

The aim was to send a crew of three astronauts to the lunar surface and back by August 1967. The plan intended to use a lifting-body spacecraft based on Boeing's Dyna-Soar delta-winged space plane program, which was cancelled in 1963. Using an Atlas rocket, it would begin with five test flights of scale models of the vehicle, followed in 1964 and 1965 with full-scale unmanned and then manned missions. Further tests would culminate in a robotic landing craft that would deliver cargo to the Moon in July 1966.

A circumlunar mission carrying astronauts would occur in September 1966, and only after further robotic testing of the whole system would astronauts go to the Moon. In 1968 a mixture of manned and cargo-delivering vehicles would establish an underground 21-person Moon base by July 1968. The project, like Project Horizon, was quickly rejected in favour of NASA's Apollo.

"The fact that these various ideas went nowhere is completely unsurprising. It took a very special set of political and international circumstances in 1961 to motivate the Kennedy administration to spend billions on a landing program," says Michael Neufeld, senior curator at the Smithsonian's National Air and Space Museum in Washington DC.

Although these projects came to nothing, they did have a major influence on determining the best way to get to the Moon. They certainly focused the debate over using a direct ascent, EOR or LOR technique to achieve a Moon landing. Once the LOR technique was agreed on by NASA, it determined the type of vehicles and techniques that needed to be built and tested to visit the Moon in the timeline dictated by Kennedy.

**Nigel Watson**
*Space science writer*
Nigel has written extensively about science and technology, in particular about extraterrestrial contact. He is the author of four books on alien life.

# RISE OF THE EXOPLANET HUNTER

## The next generation of alien-world-seeking spacecraft will revolutionise our understanding of distant planets

Reported by Baljeet Panesar

Almost 30 years ago, two astronomers changed the way we viewed our place within the universe. They had discovered the first extrasolar planets, or exoplanets - planets that orbit stars other than our Sun. Since then we have discovered over 4,300 new and fascinating worlds - planets that orbit two stars, a planet that is so close to its host star that it's being ripped apart and a planet that's covered in hot lava. Some even orbit stars like our Sun in the habitable zone where liquid water could exist - and there are hundreds of billions of intriguing new worlds in the Milky Way alone that are yet to be discovered and explored.

To explore these unknown worlds, the Atmospheric Remote-sensing Infrared Exoplanet Large-survey, or Ariel, is set to launch at the end of the decade. The mission was selected by the European Space Agency (ESA) as its third dedicated exoplanet hunter to launch within ten years, and the fourth 'medium-class' project in the Cosmic Vision program, back in 2018 after beating a mission to study energetic particles around the Earth and an X-ray telescope. For the past five years, scientists have been working on Ariel's science goals and instruments, which has involved collaboration between more than 50 institutes in 17 countries. NASA will also contribute an instrument to the mission.

Ariel will address one of the key themes of the ESA's Cosmic Vision program: what are the conditions for planet formation and the emergence of life? "Ariel will study what exoplanets are made of, how they formed and how they evolve by surveying a diverse sample of about 1,000 extrasolar planets in visible and infrared wavelengths simultaneously. It is the first mission dedicated to measuring the chemical composition and thermal structures of hundreds of transiting exoplanets, enabling planetary science far beyond the boundaries of the Solar System," says Professor Günther Hasinger, the ESA's director of science.

In recent years we have made great progress in the study of exoplanets. However, Ariel is different to the other exoplanet missions that have been launched in the past. "Previous space observatories like Kepler, CoRoT [Convention, Rotation and planetary Transits] and TESS [the Transiting Exoplanet Survey Satellite] focused on discovering new exoplanets" says Dr Subhajit Sarkar, a research associate at Cardiff University in the UK, who works on the Ariel mission. "Unlike previous missions, Ariel does not aim to discover new planets, but instead will characterise the atmospheres of known exoplanets," continues Sarkar.

"ARIEL WILL STUDY WHAT EXOPLANETS ARE MADE OF, HOW THEY FORMED AND HOW THEY EVOLVE" GÜNTHER HASINGER


# THE ARIEL MISSION

Inside the planet explorer that could transform exoplanet science

**1 FINE GUIDANCE SYSTEM**
The onboard guidance system will allow Ariel to guide and focus itself on target exoplanets with high precision and stability.

**2 HIGH-GAIN ANTENNA**
Using the X-band frequency range, this is the main method of communication to and from Ariel.

**3 THE ARIEL INFRARED SPECTROMETER**
Ariel's main scientific instrument will detect molecules that are present in planets' atmospheres to work out their structure and composition.

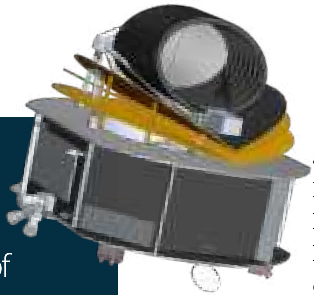
**4 THRUSTERS**
Ariel will use a hydrazine monopropulsion system to perform one manoeuvre each month so that it can maintain its orbit.

**5 SOLAR CELLS**
Located on the bottom of the spacecraft's main body, the solar cells generate about one kilowatt of power to provide Ariel with all of its power needs.

**6 TELESCOPE**
Ariel's 1.1 by 0.7 metre (3.6 by 2.3 foot) telescope will be made entirely from aluminium, and its primary mirror will be coated in silver.

**7 PAYLOAD MODULE**
Ariel's telescope, instruments and guidance system are cooled to -328 degrees Celsius (-559 degrees Fahrenheit).

**8 SERVICE MODULE**
This contains everything that Ariel needs to operate at a temperature between -20 and 50 degrees Celsius (-4 and 122 degrees Fahrenheit).



## ARIEL'S OBJECTIVES

The main aims of the ESA's new exoplanet explorer

### 1 TO DISCOVER WHAT EXOPLANETS ARE MADE OF

Ariel is the first mission dedicated to measuring the elemental composition and thermal properties of known exoplanets.

### 2 TO DETERMINE HOW PLANETS AND PLANETARY SYSTEMS FORM

Observing hot worlds will give us insights into the early stages of planet formation and their first few million years.

### 3 TO WORK OUT HOW PLANETS AND THEIR ATMOSPHERES EVOLVE OVER TIME

Ariel will observe the 'chemical fingerprint', or spectra, of a planet's atmosphere. From this data the composition, temperature and physical processes can be determined.

The Ariel mission will focus on surveying hot and warm giants similar in size to Jupiter and Neptune to super-Earths that orbit close to their host stars, analysing a range of spectral types from hotter Sun-like, white-yellow dwarf stars to red dwarfs. Hot exoplanets, some which reach over 2,000 degrees Celsius (3,632 degrees Fahrenheit), are ideal for studying the chemistry and formation history of the planet because gases continuously circulate throughout the atmosphere, preventing the formation of layers of clouds via condensation.

Exoplanet missions are extremely important and can help us to understand our own origins and the origins of the universe. "Exoplanet studies are one of the most important and appealing fields of contemporary astrophysics," says Hasinger.

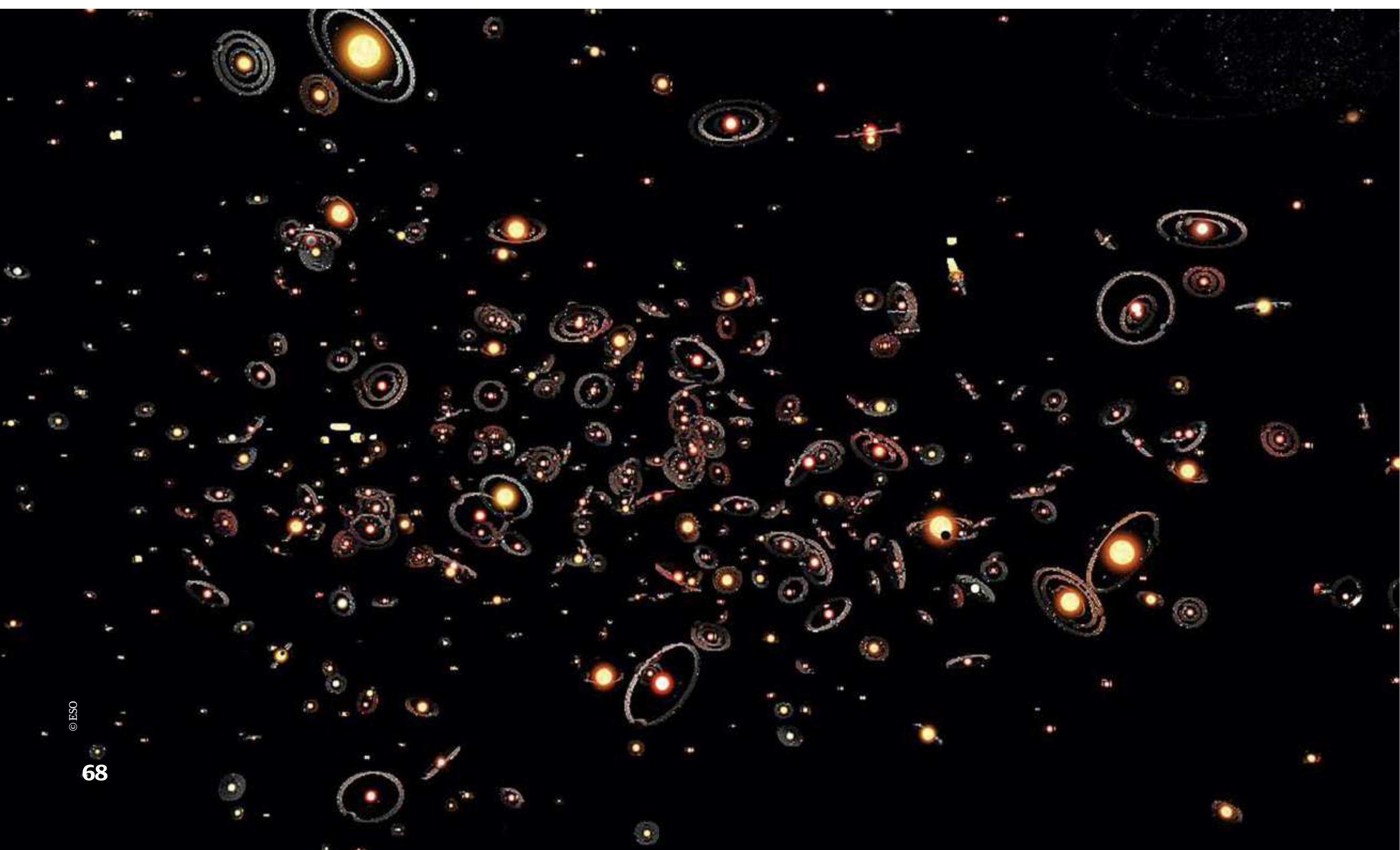
"We study exoplanets for several reasons," says Sarkar. "Firstly, to understand our own origins. Where did we come from? How did the Solar System form? What led to the formation of the Earth and the origins of life on Earth? Exoplanets allow us to test the theories of planet formation through multiple natural experiments instead of using the example of one we had before".

Although so far we have found no evidence to suggest that there is life beyond planet Earth, Ariel will rise to the challenge. "Exoplanets are part of the search for life in the universe and the age-old question of 'are we alone?' We may be able to detect biosignatures in the spectra of these worlds that reveal the presence of life. Rocky planets that orbit in the 'habitable zone' of their star – where liquid water could possibly form on the surface of the planet – are a focus for such a search. This would be one of the greatest discoveries in science, and again place our own origins in context. It may be possible one day to find out how common life is in the universe," continues Sarkar. Understanding exoplanets can also help us "better understand the processes affecting the Earth" and "may have great relevance for understanding the future evolution of our own planet," he explains.

The space observatory is currently scheduled to start its search for life in 2029, launching with Comet Interceptor from the ESA's spaceport in Kourou, French Guiana on the new Ariane 6 rocket, which is currently scheduled to make its maiden launch in 2022. The craft will take roughly six months to reach its orbit and undergo commissioning and science demonstration phases before it can start its primary mission. The space observatory will make its way to Lagrange point 2 (L2), an orbital parking spot roughly 1.5 million kilometres (930,000 miles) from Earth. The initial science mission will last for 3.5 years, with the possibility of a two-year extension.

Once Ariel is in position, the observatory will use its 0.9-metre (three-foot) diameter primary mirror to collect light from faraway stars in the visible and infrared wavelengths. Other instruments,

**Below:** It is estimated that every star in our galaxy has at least one planet in orbit



including an infrared spectrometer and photometer, will perform spectroscopic analyses on the target exoplanets. A spectrum will be obtained for each target exoplanet, and like its predecessors, Ariel will make use of the transit method to study exoplanets, where the dip in starlight is measured as a planet travels in front of its host star. Sarkar explains: “Each observation will involve measuring the light from the host star for a period of time, during which the planet will transit, producing a ‘light curve’. The spectrometers allow the light to be split into different wavelengths so that multiple light curves can be obtained as a function of wavelength. The ‘dip’ in the starlight is proportional to the planet-star area ratio and returns a planet radius with wavelength.

“While the bulk of the radius value is due to the planet body and fixed, a small amount of extra absorption occurs due to molecules in the atmosphere of the planet. These molecules absorb differently at different wavelengths, each with its own characteristic spectral ‘fingerprint’. By tracing out the apparent radius variation with wavelength we obtain a ‘transmission spectrum’ of the atmosphere. By analysing this we can find the molecules making up the atmosphere and other properties such as temperature and the presence of clouds and hazes.” Results from Ariel will be made available to the science community and the general public almost immediately. It is hoped that this approach will ensure that the Ariel mission will outperform its mission goals.

In recent years our understanding and knowledge of exoplanets has grown exponentially, and Ariel will surely further our understanding even more, perhaps more than we could ever hope or imagine, and might also help to explain our weird Solar System. “We know that planets are common around all types of stars. However, this planet population is very diverse, covering different sizes, masses, temperatures and orbital parameters. The architectures of most of these planetary systems also do not match that of our Solar System, and there are planet types, such as super-Earths and mini-Neptunes that do not occur in our own Solar System. Therefore the theories that were developed to explain the Solar System planets do not completely explain these new exoplanetary systems. We would like to understand how this complex pattern arises,” explains Sarkar.

The most famous – and arguably the most successful – use of the transit method was by NASA’s Kepler space telescope, which was launched in 2009. In just under ten years the number of known exoplanets rapidly grew from a few dozen to a few thousand. Over the course of its lifetime Kepler observed over 530,000 stars, looking for

## HOW TO CHARACTERISE AN EXOPLANET

Ariel uses a well-established and effective method to study exoplanets

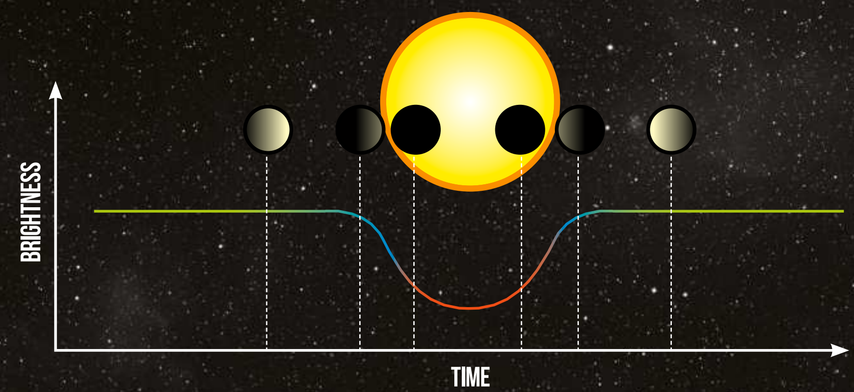
**EYES ON THE SKY**
Ariel’s primary mirror will collect visible and infrared light from distant star systems and focus it onto the spectrometers.

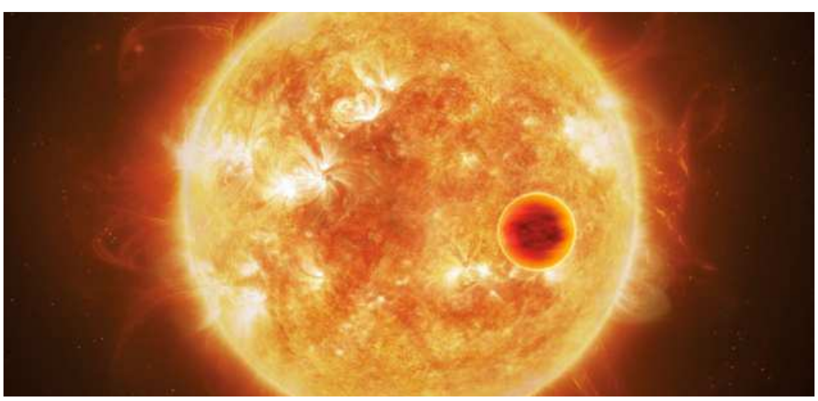
**ARIEL’S SPECTROMETERS**
These will separate light into a rainbow to create a chemical fingerprint of a planet, detecting well-known and more exotic elements in the atmosphere.

**SEARCHING FOR A DIP**
Ariel finds planets by using the transit method. When a planet passes in front of its star, it blocks some of the star’s light, producing a dip in the light curve.

**ESTIMATING PLANET PROPERTIES**
Astronomers can estimate the orbit and mass of the exoplanet by measuring the frequency and amount of dimming.

**EXOPLANET CENSUS**
After studying the stars and planets of other distant planetary systems, Ariel will help us to better understand our cosmic neighbourhood.

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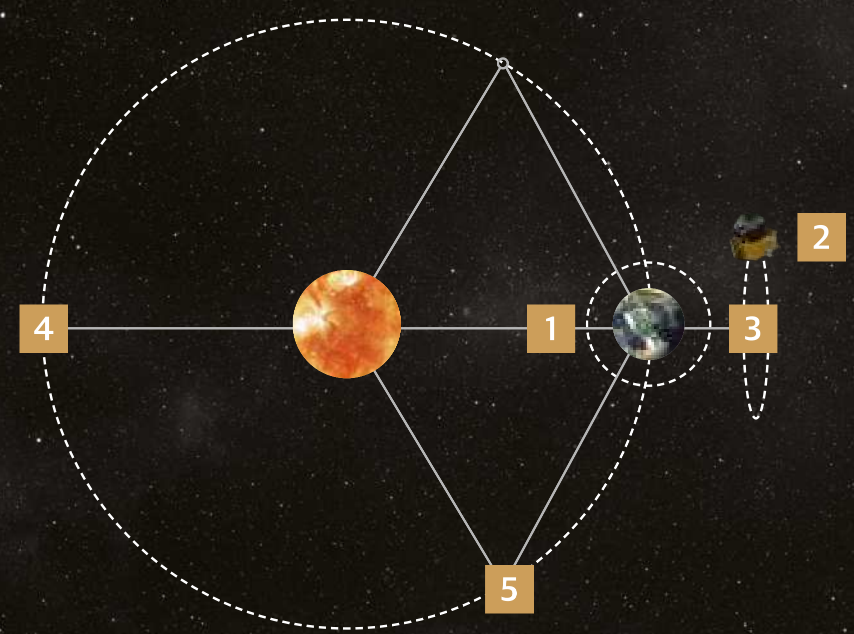
© NASA/JPL-Caltech

**Top:** Ariel will be the first space telescope to probe the atmospheres of strange worlds, focusing on hotter planets

**Left:** An artist’s impression of what the TRAPPIST-1 system looks like from TRAPPIST-1f

# ARIEL'S OBSERVING SPOT

The space observatory's home is perfectly positioned for searching for alien worlds




**1 OBSERVING THE SUN**
Partway between the Sun and Earth is Lagrange point 1, where the Sun can be observed without interruptions.

**2 ARIEL'S ORBIT**
The Ariel spacecraft will be placed in an orbit that is 1.5 million kilometres (930,000 miles) from Earth for at least four years.

**3 A GRAVITATIONAL BALANCING ACT**
Sitting at Lagrange point 2, Ariel is shielded from the light of the Sun and has a clear view of the entire sky for exoplanet observations.

**4 THE SUN'S FAR SIDE**
Hidden behind the Sun on the opposite side of Earth, this point hasn't yet been used by space observatories.

**5 THE LAGRANGIAN TROJANS**
Stable points that lie 60 degrees ahead (L4) and behind (L5) Earth. Dust and asteroids accumulate in this region.

the characteristic dips in starlight. Analysis of data from Kepler suggests rocky, Earth-like planets are common, that planets and solar systems are very diverse and that planets can develop around stars that are very different to our Sun.

Kepler's successor, NASA's Transiting Exoplanet Survey Satellite, or TESS, was specifically designed to search for Earth-sized planets that orbit stars that are less than 300 light years from Earth. After monitoring more than 200,000 stars and covering an area of sky 400-times larger than Kepler, TESS has so far discovered over 95 new worlds. Hundreds – if not thousands – more will continue to be discovered over TESS' extended mission. Most of these new worlds are larger than the Earth but smaller than Neptune.

Ariel will revolutionise what we understand about exoplanet atmospheres, and scientists are already excited. "Just like Kepler transformed our understanding of exoplanet demographics, I believe Ariel will be transformative for the field of exoplanet science. No other mission will produce the number of spectra that Ariel will, which will allow us to answer population-based questions about formation and evolution, as well as unprecedented insight into the physics and chemistry of exoplanet atmospheres," says Sarkar.

"Ariel is the first large spectroscopic survey of exoplanets, and as a result we are pioneering methods and statistical techniques that will be applicable to future exoplanet surveys, including those that may focus on habitable worlds and the search for life. I am excited about the possibilities of using the data to constrain the various theories we have for planet formation and evolution, leading to a 'theory of everything for planets'. However, perhaps even more exciting will be discovering the things we didn't think about or never knew could occur," Sarkar continues.

For thousands of years, humans have looked up at the sky in awe of the stars. In our quest to satisfy our curiosity we have built rockets, spacecraft and telescopes to explore the farthest reaches of the cosmos. In just 30 years we have learned so much about exoplanets, but this decade promises to reveal even more about these alien worlds. We may be getting closer than ever before to finally finding the answer to the ultimate question: are we alone in the universe?


**Baljeet Panesar**
*Research Editor*
Baljeet holds a degree in chemistry and serves as the Research Editor on **All About Space** and its sister title **How It Works**.


**Right:** Double sunsets like that on the *Star Wars* world of Tatooine may be just as common as those on single-Sun worlds

© NRAO

# MEET THE EXOPLANET HUNTERS

The current and future spacecraft that will search for and characterise strange worlds in this decade and beyond

## TESS

**Date launched:** 18 April 2018

**Mission ended:** Primary mission ended on 4 July 2020; its extended mission ends in 2022

**Main objective:** To search for planets around nearby bright stars

**Most notable achievement:** Identifying an Earth-like planet, called TOI 700 d, within the habitable zone

Over the course of two years, TESS imaged about 75 per cent of the sky. Using four cameras, it imaged each 'sector' of the sky for about a month, spending the first year imaging the southern sky and its second imaging the northern sky.

© NASA

## CHEOPS

**Date launched:** 18 December 2019

**Mission ended:** Primary mission ended after 3.5 years

**Main objective:** To characterise the size of known exoplanets that orbit nearby bright stars

**Most notable achievement:** Discovering one of the hottest and most extreme planets to date – WASP-189b

The CHaracterising ExOPlanets Satellite is the first-ever mission dedicated to studying nearby stars that are known to host exoplanets. It will focus on about 500 Earth to Neptune-sized planets.

© Nicholas Forder

## JWST

**Date launching:** 31 October 2021

**Mission ended:** N/A

**Main objective:** The JWST will characterise the atmospheres of known exoplanets

**Most notable achievement:** N/A

The James Webb Space Telescope will probe the atmospheres around rocky exoplanets using transits and direct imaging. This new pair of eyes will scan the sky in infrared – wavelengths that exoplanets haven't previously been seen in – to reveal more about their nature.

© Adrian Mann

## NANCY GRACE ROMAN SPACE TELESCOPE

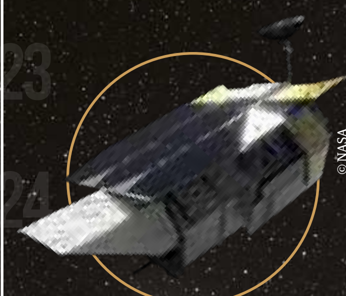
**Date launching:** 2025

**Mission ended:** N/A

**Main objective:** To search for rocky exoplanets in and beyond the habitable zone

**Most notable achievement:** N/A

Roman will use a microlensing technique to survey 100 million stars. This technique will allow it to scour for 2,500 planets that orbit their star closer than Venus and farther than Pluto and are smaller in size than Mars.



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## PLATO

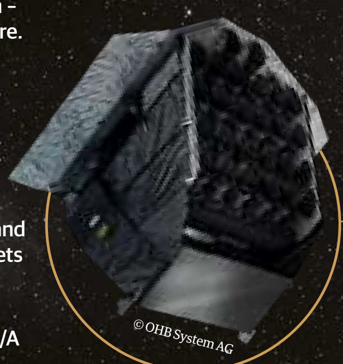
**Date launching:** 2026

**Mission ended:** N/A

**Main objective:** To search for and characterise Earth-like exoplanets that sit in the habitable zone of Sun-like stars.

**Most notable achievement:** N/A

The PLAnetary Transits and Oscillations of stars craft will watch hundreds of thousands of stars in this four-year mission. PLATO will provide information, such as an exoplanet's radius, density and stellar irradiation, to determine whether it could be habitable.



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## ARIEL

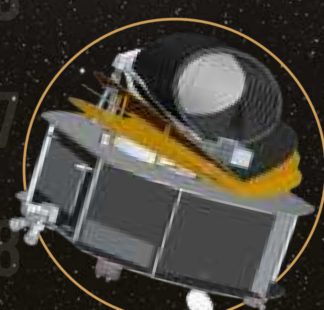
**Date launching:** 2029

**Mission ended:** N/A

**Main objective:** Perform a large-scale survey of a wide range of exoplanets and analyse their compositions and atmospheres

**Most notable achievement:** N/A

This four-year mission will target roughly 1,000 exoplanets, focusing on hot and warm gas giants, super-Earths, mini-Neptunes and Earth-sized planets. Ariel is the first space telescope that is solely dedicated to the study of exoplanet atmospheres.



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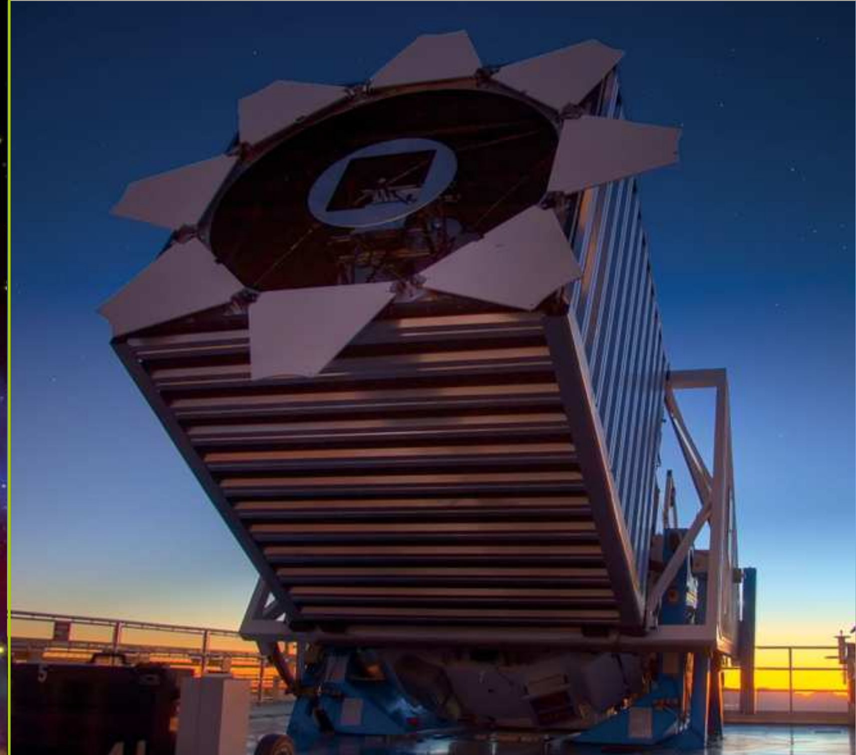
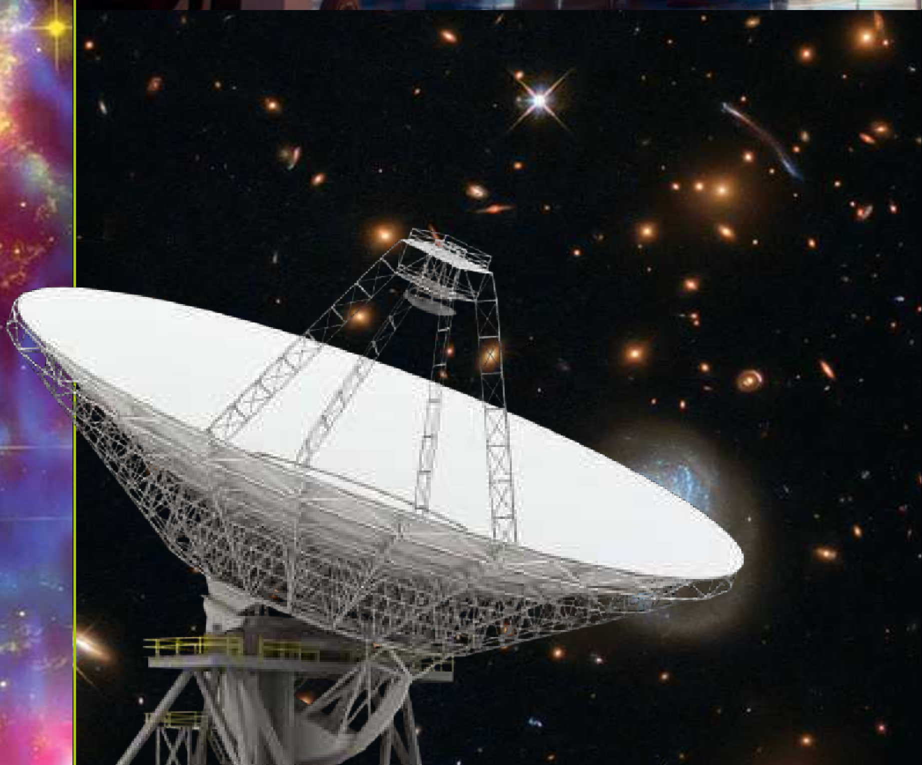
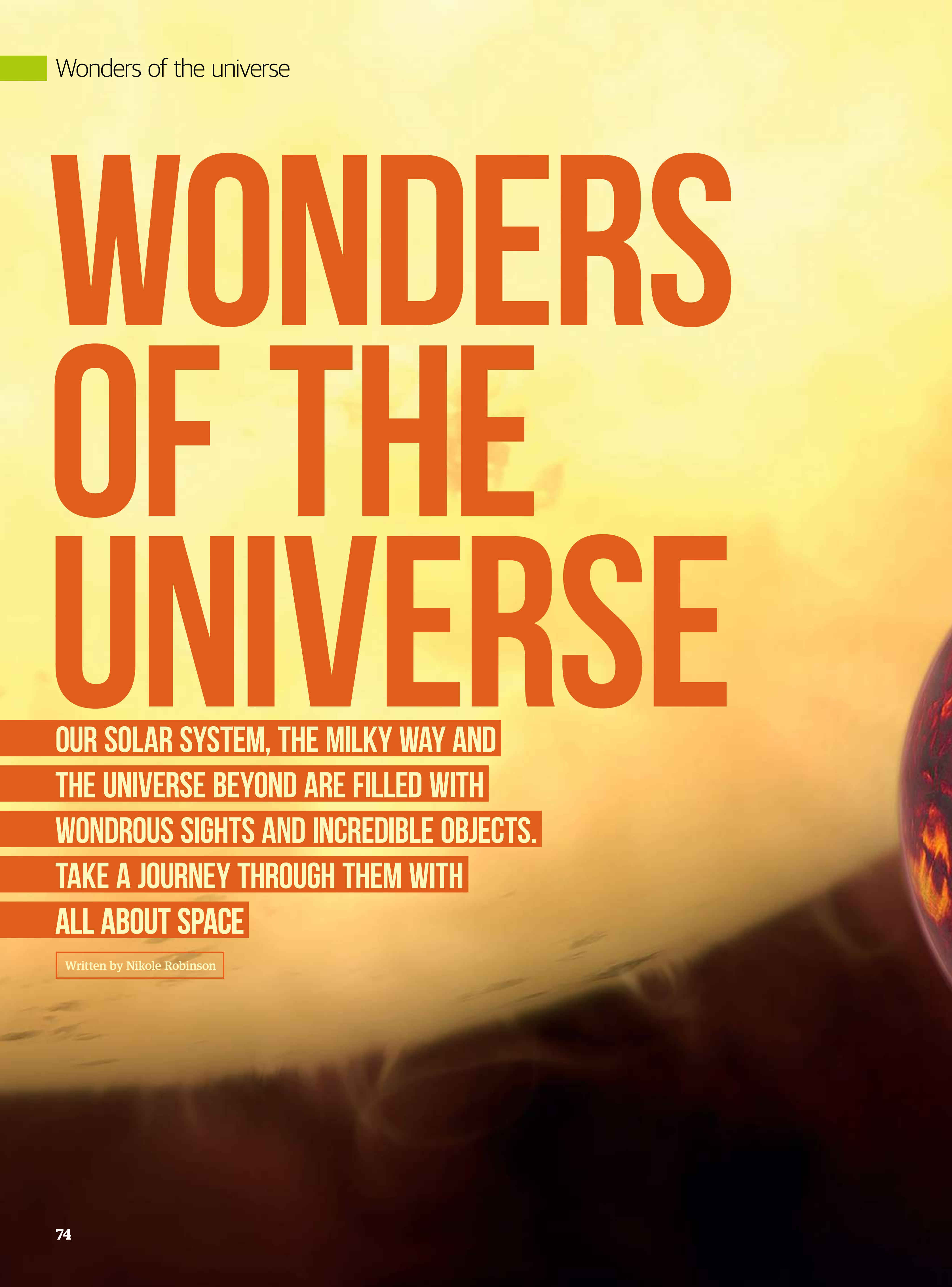
# Deep Space

## Go beyond the Milky Way and uncover the mysteries of the universe





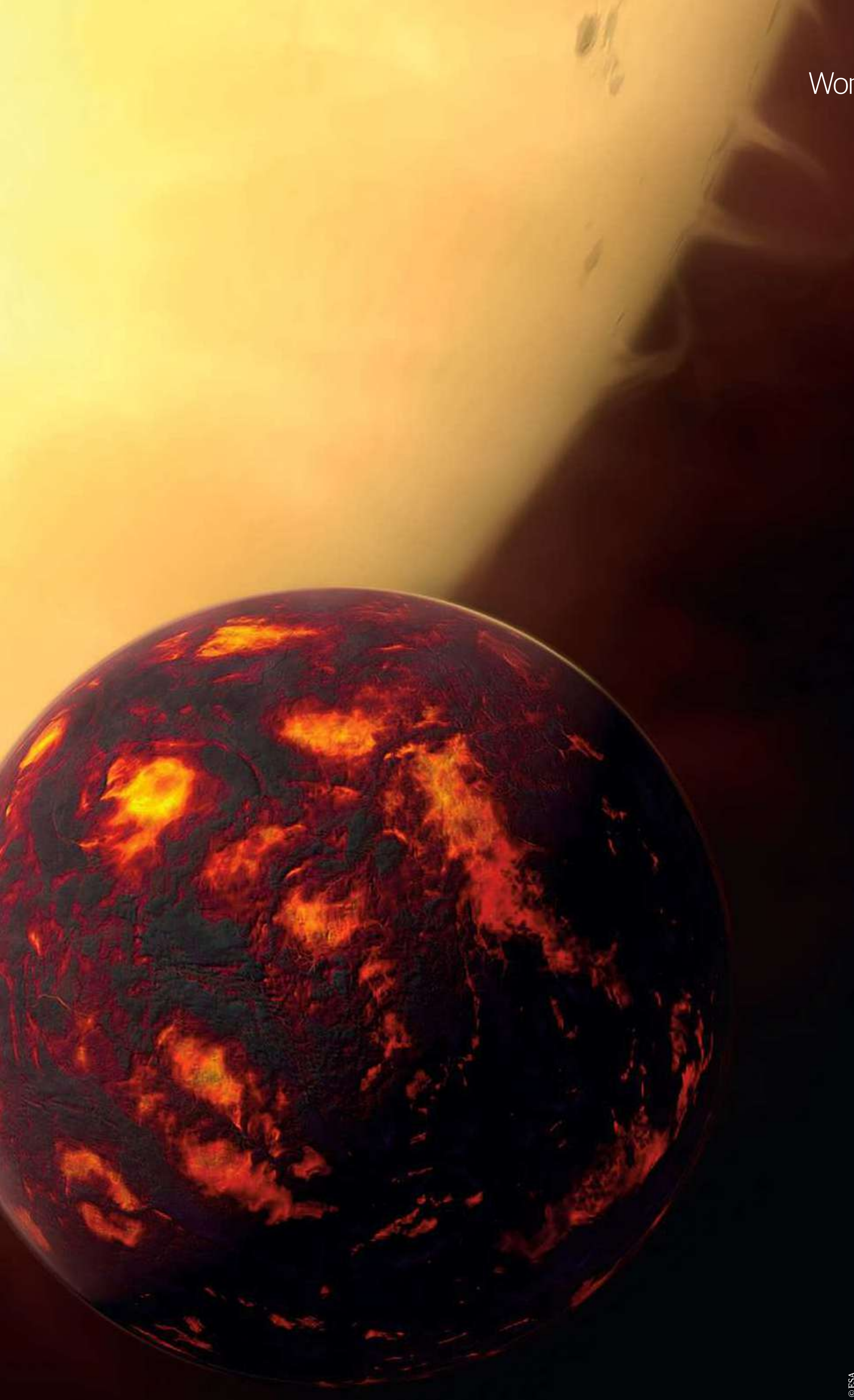
“The youngest known supernova remnant”



# WONDERS OF THE UNIVERSE

**OUR SOLAR SYSTEM, THE MILKY WAY AND THE UNIVERSE BEYOND ARE FILLED WITH WONDROUS SIGHTS AND INCREDIBLE OBJECTS. TAKE A JOURNEY THROUGH THEM WITH ALL ABOUT SPACE**

Written by Nikole Robinson



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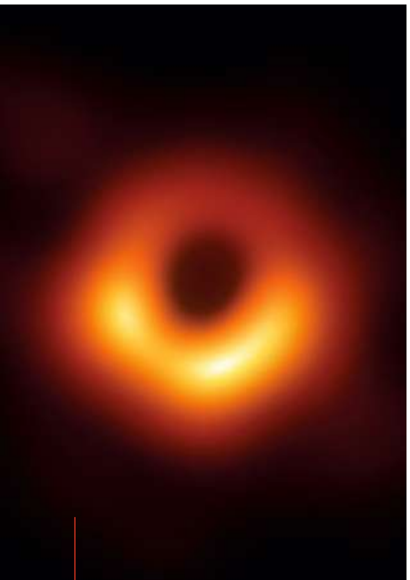
# THE DIAMOND PLANET

One of five known planets in orbit around the larger star of a binary pair just 41 light years away from the Sun in the constellation of Cancer, 55 Cancri e is a super-Earth with a speedy orbital period of just 18 hours. As the planet closest to its host star, pressures and temperatures are high, and it is likely tidally locked to its parent body, meaning the same side is constantly facing it.

Studies revealed that the planet has a mass about eight times that of Earth, and a radius twice as wide. Indirect analysis of the planet's composition revealed it has a huge abundance of carbon. Scientists posit that the surface of the planet is covered in graphite, which protects a much more interesting layer of pure diamond underneath, with the rare material accounting for about a third of the planet's mass. If this diamond-encrusted theory proves correct, the planet would be worth around $26.9 nonillion (£19.3 nonillion).



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## BLACK HOLE REVELATION

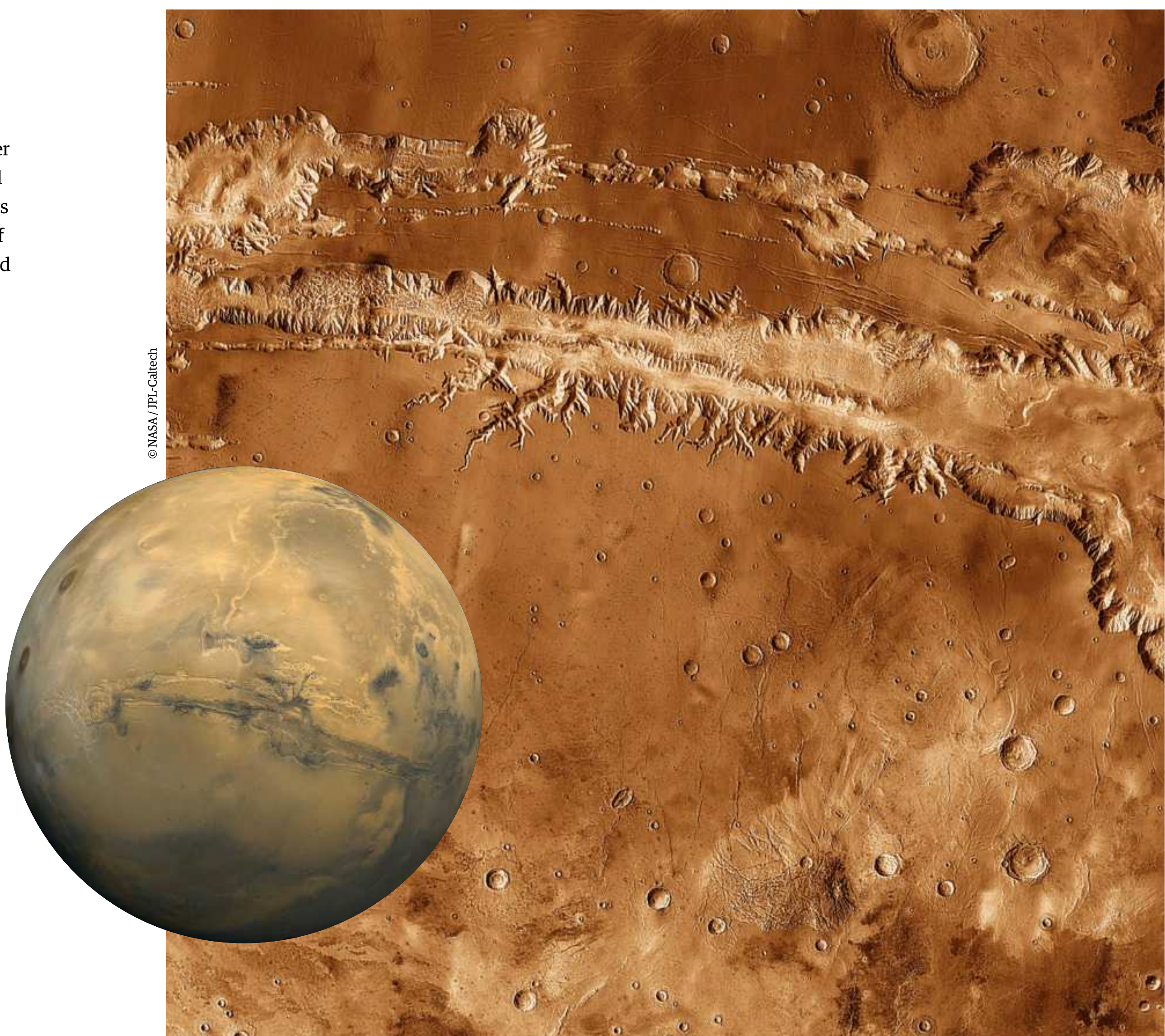
Though it's impossible to image a black hole because of their very nature, that didn't stop scientists setting their sights on the supermassive black hole at the centre of Messier 87, a galaxy around 53 million light years from Earth. Using a network of telescopes spanning the entire globe – collectively called the Event Horizon Telescope – combined with a clever computer algorithm, researchers produced this image of the superheated gas swirling around the silhouette of the black hole itself. The captured material appears brighter on one side due to the fact that it is orbiting the massive object – emissions are boosted by the Doppler effect as the material swings towards Earth.

The shadowy object at the centre weighs a whopping 6.5 billion solar masses, while the event horizon – the point at which nothing can escape the gravitational influence of a black hole – spans across 38 billion kilometres (24 billion miles). The first direct image of a black hole lined up perfectly with predictions of how these gargantuan galaxy gobblers might look, and supports Einstein's theory of general relativity.

© NASA

## A MOON WITH PLUMES

The Cassini mission to Saturn revealed its sixth-largest moon, Enceladus, to be a much more interesting place than expected – and also one of the best places in the Solar System to search for life. Perhaps most intriguing is the eruption of geyser-like plumes from the moon's south polar region, spewing water vapour and ice particles from a salty subsurface ocean ten kilometres (six miles) deep, trapped below the icy surface. Cassini flew through the plumes seven times over its 13-year mission. Analyses of the plume material found frozen salt water, methane, heavy organic molecules containing carbon and hydrogen and silicon-bearing grains. It's believed the material ejected in the plumes is responsible for both replenishing the moon's bright surface and contributing material to Saturn's E ring, in which the moon orbits.



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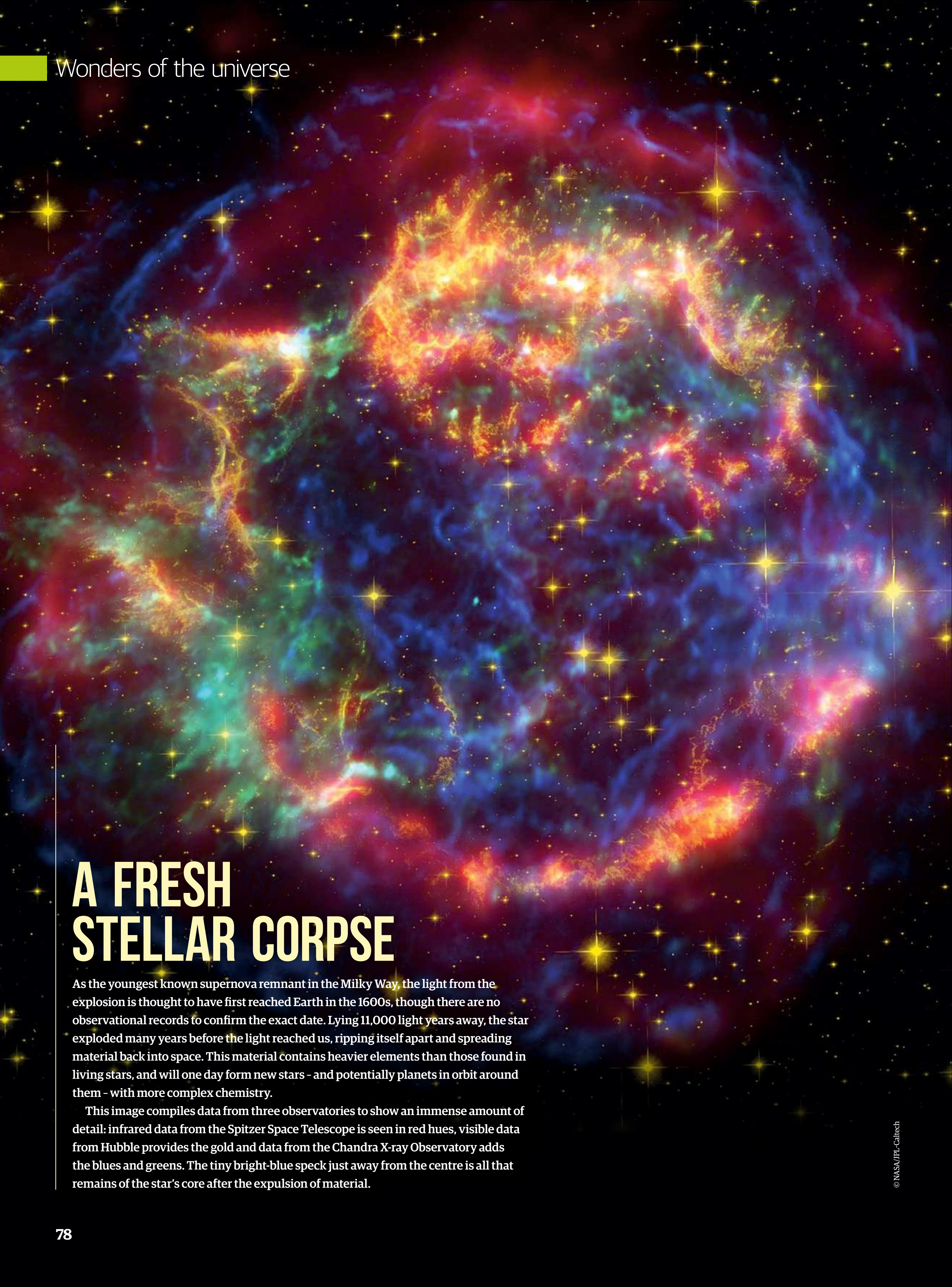
## SUCKED INTO THE WHIRLPOOL

The Whirlpool Galaxy is a popular target for amateur astronomers in Canes Venatici. Although this striking spiral is interesting enough on its own, it is currently in the process of absorbing its dwarf companion NGC 5195, the yellowish object seemingly clinging to one of the Whirlpool's arms on the right. The smaller galaxy has been on a collision course with its neighbour for half a billion years, and currently lies behind it as seen from Earth, evident by the star bridge that links the pair blocking some of its light. In this Hubble image of the pair, red highlights the hydrogen within star-forming regions, blue marks hot, young stars while the yellow shows older stars.

## A GRANDER CANYON

The Red Planet not only hosts the tallest mountain in the Solar System, Olympus Mons, but also a vast canyon that runs across almost one-fifth of the planet's entire circumference: Valles Marineris. Scarring the surface east of the Tharsis region, this huge crevice is 4,000 kilometres (2,500 miles) long, 200 kilometres (120 miles) wide and up to seven kilometres (4.3 miles) deep. For comparison, Arizona's Grand Canyon is a mere 446 kilometres (277 miles) long and 1.6 kilometres (one mile) deep.

Though the Earthly equivalent was cut by the Colorado River over millions of years, Mars' potential past water is not believed to have formed the valley – though some channels on the eastern flank may have been formed by flowing water. The leading theory is that Valles Marineris is a tectonic crack in the Martian crust formed when the planet cooled, widened by marsquakes and erosion. This is a composite mosaic of images taken by the 2001 Mars Odyssey orbiter's Thermal Emission Imaging System (THEMIS) camera.



# A FRESH STELLAR CORPSE

As the youngest known supernova remnant in the Milky Way, the light from the explosion is thought to have first reached Earth in the 1600s, though there are no observational records to confirm the exact date. Lying 11,000 light years away, the star exploded many years before the light reached us, ripping itself apart and spreading material back into space. This material contains heavier elements than those found in living stars, and will one day form new stars – and potentially planets in orbit around them – with more complex chemistry.

This image compiles data from three observatories to show an immense amount of detail: infrared data from the Spitzer Space Telescope is seen in red hues, visible data from Hubble provides the gold and data from the Chandra X-ray Observatory adds the blues and greens. The tiny bright-blue speck just away from the centre is all that remains of the star's core after the expulsion of material.

© NASA

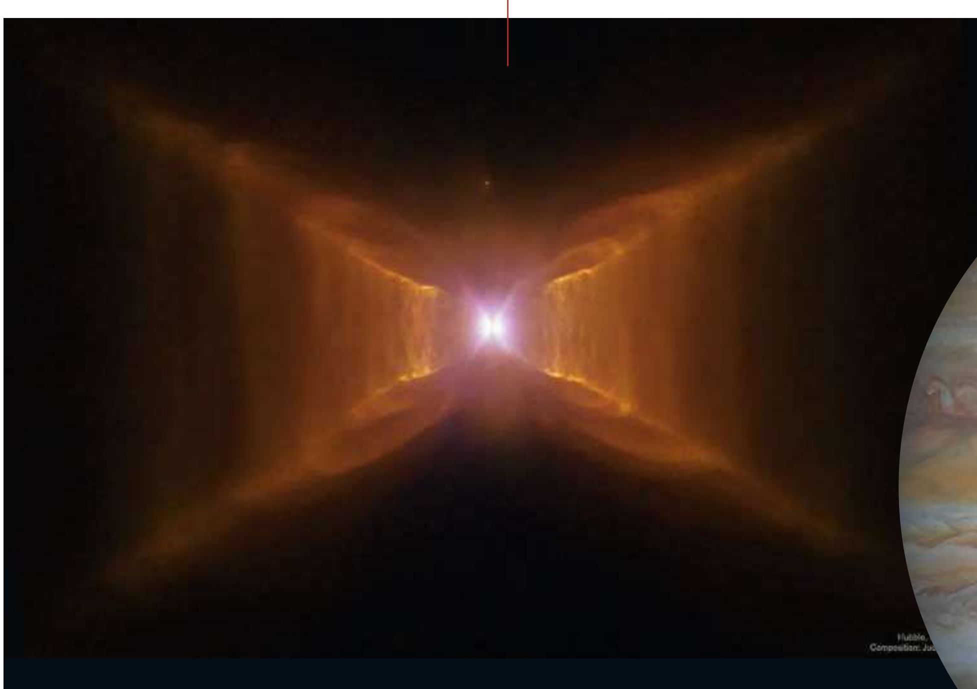
# SUPER SATURN

Saturn is well known for its vast system of rings, composed of icy and rocky material. In 2012 the first detection of an exoplanet supporting a similar ring system was made using the transit method when the bands encircling the potential planet, dubbed J1407b, eclipsed their Sun-like host star for several days – and later studies have shown that this system of rings is far more expansive than Saturn's.

Consisting of at least 30 separate rings, the system has a diameter of almost 120 million kilometres (74.5 million miles), 200 times that of the Saturnian system. J1407b is likely a giant planet with a mass of between 13 and 26 Jupiter masses, while the particles that make up the ring system have a similar mass to Earth. A gap in the ring system around 61 million kilometres (38 million miles) from the centre highlights the possibility of an exomoon in orbit.

# RED RECTANGLE

This unusual, X-shaped protoplanetary nebula radiates from a close binary star system called HD 44179, and was discovered around the pair by an infrared sky survey in 1973. Lying 2,300 light years away in the constellation of Monoceros, it's still unknown what causes the red colour of the nebula, but its shape is thought to be caused by the outflowing of stellar material from the binary pair at the centre as they shed their outer layers in their final stages of life. The cone-like structures on either side show how material is being ejected in two opposing directions. The rung-like features that can be seen vertically crossing the cones on both sides – giving the Red Rectangle Nebula the unique appearance of a spider's web – are evidence of episodes of mass ejection, where an outpouring of material is ejected every few hundred years.



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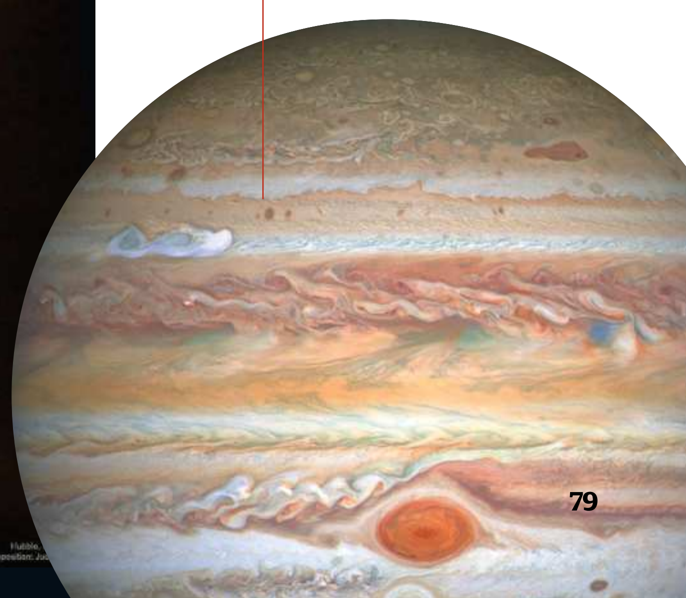
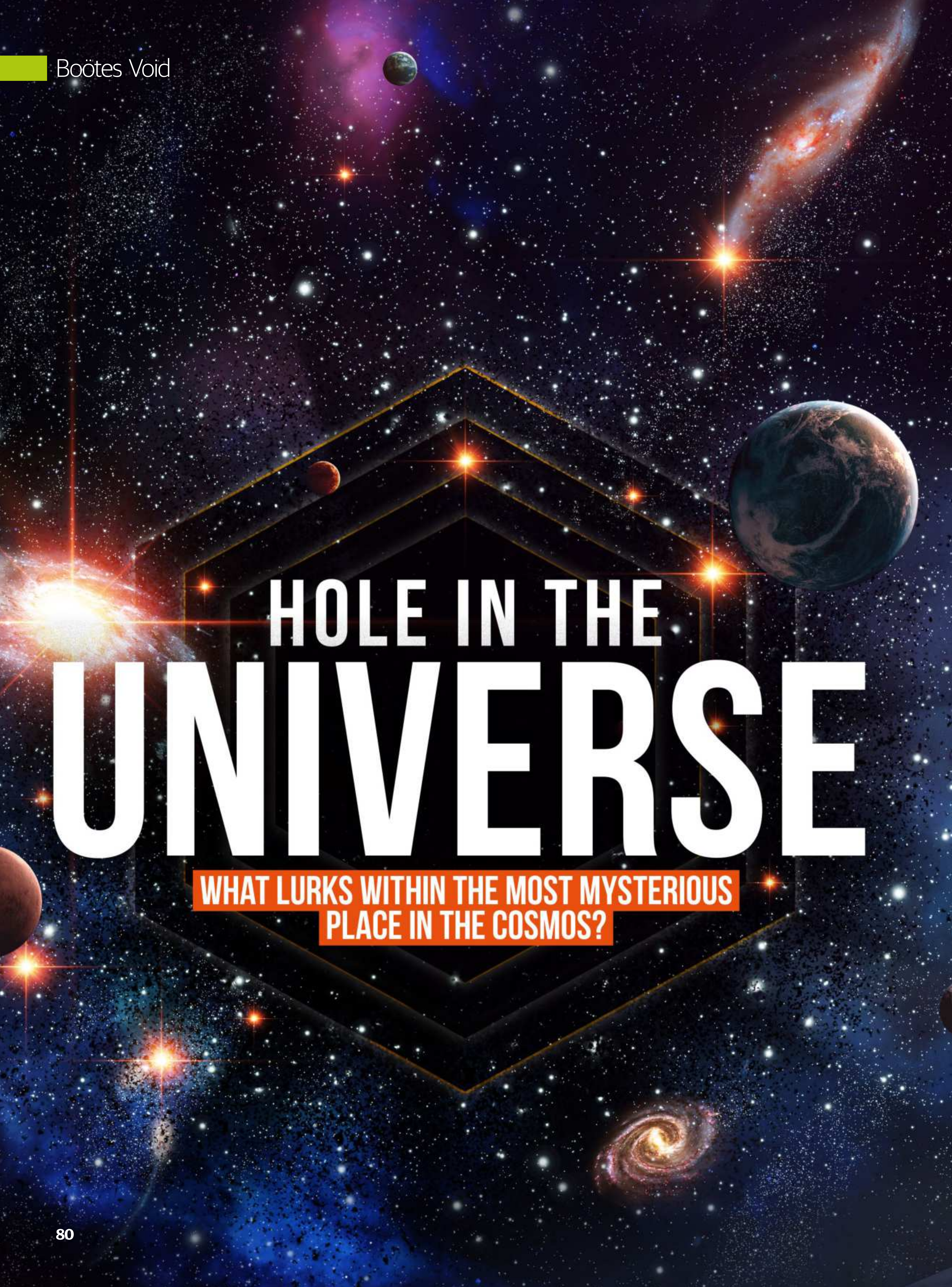
# A GIANT RED STORM

The king of the Solar System is covered with tempestuous, caramel-coloured cloud bands, but its most prominent feature is the red, oval-shaped storm known as the Great Red Spot (GRS). Swirling at speeds of up to 432 kilometres (268 miles) per hour between two jet streams in the planet's southern hemisphere, even after sending two probes to orbit the gas giant, scientists still aren't sure what causes the storm's conspicuous colour.

The largest storm in the Solar System, the GRS has been continuously observed since 1879, though it was recorded earlier in 1831. Rotating counterclockwise with a period of around six Earth days, the GRS measured 16,350 kilometres (10,160 miles) across in 2017 – 1.3 times the diameter of Earth – though it appears to be shrinking. NASA's Juno spacecraft captured this close-up of the storm on 1 April 2018 as it made its 12th close flyby of the planet, when the spacecraft skimmed 24,749 to 49,299 kilometres (15,379 to 30,633 miles) above the tops of the Jovian clouds.





# HOLE IN THE UNIVERSE

**WHAT LURKS WITHIN THE MOST MYSTERIOUS PLACE IN THE COSMOS?**

"If the Milky Way had been in the centre of the Boötes Void , we wouldn't have known there were other galaxies until the 1960s." This was a quote from American astronomer Greg Aldering in an article for *Discover* magazine in 1995. He was talking about a region of space that appears to be a cosmological 'dead zone', containing very few stars or galaxies.

Galaxies have been observed for hundreds of years with telescopes, while some, such as Andromeda, Triangulum and the Magellanic Clouds, have been visible to the naked eye throughout human existence. But inside a cosmic void such as Boötes, none of that would have been the case until the development of modern instruments. The Milky Way would have been an anomaly inside a dark bubble of 'nothing'. As it happens, our galaxy exists among others in a cluster, called the Local Group.

The first void was discovered in 1978 by two separate teams: one at the Kitt Peak National Observatory in Arizona, and the other at the Tartu Astrophysical Observatory in Estonia. Looking at the foreground region of Abell 1656 and Abell 1367 – together called the Coma Supercluster – 300 million light years away, they noticed an unusual absence of galaxies.

Then, in 1981, Robert Kirshner and others discovered a large galaxy-free zone centred 700 million light years away in the constellation of Boötes. Looking at the redshift of surrounding galaxies – the degree to which galaxies' light spectra are reddened due to their recession speeds, and thus distances, a result of the expansion of space – they noticed a gap at around 1,500 kilometres (932 miles) per second. Follow-up work constrained this to 1,200 to 1,900 kilometres (745 to 1,180 miles) per second. There were very few galaxies with those velocities. This roughly spherical 330 million light year expanse, disguised by surrounding galaxies, had finally shown itself.

The Boötes Void is roughly 3,300 times the size of the Milky Way, and is sometimes called a 'supervoid'. If the entire observable universe was one metre (3.2 feet) wide, then Boötes would span about 2.7 millimetres (0.1 inches). In cosmological terms, that's vast. By 1997 a total of 60 galaxies had been discovered within – roughly 33 times fewer than would normally be expected for other parts of space. Boötes isn't truly barren, but it isn't lush.

# INGREDIENTS OF THE UNIVERSE VS VOIDS

## THE UNIVERSE

### Dark matter

Sites of invisible dark matter were the gravitational 'seeds' that attracted the universe's primordial hydrogen and helium gas. This dark matter formed shortly after the Big Bang.

### Gas

Largely made of primordial hydrogen (75 per cent) and helium (24 per cent), gas concentrates in cosmic filaments, where large concentrations of dark matter are already present. This then collapses to form galaxies full of stars.

### Dust

When the largest stars explode as supernovae, they spread heavy elements into intergalactic space. Some of this forms into molecules, including organic compounds. Some then forms into dust grains.

### Stars

Residing in the stellar metropolises of galaxies, stars illuminate a web-like structure on the largest cosmic scales, consisting of clusters, filaments, arcs, sheets and walls.

## VOIDS

### Dark energy

Dark energy, comprising 68 per cent of the universe's energy density, is responsible for the accelerated expansion of space. Changes in a void's shape will partly be down to dark energy.

### Neutrinos

Because they hardly interact with normal matter, neutrinos travel the entire universe almost unhindered. But their masses can affect the number of small and large voids, something that is being explored further.

### Dwarf galaxies

Of the few galaxies that do reside in voids, many – if not all – are dwarf galaxies with slow evolutions.

> "DEEP INSIDE WE DO FIND SOME MATERIAL, LIKE DARK MATTER AND SMALL, DIM DWARF GALAXIES" PAUL M. SUTTER

But are voids fundamentally different from other areas of space? "Voids are almost completely empty. You can go millions of light years without encountering anything more than a hydrogen atom," says cosmologist, science educator and author Paul M. Sutter. "But deep inside we do find some material, like dark matter and small, dim dwarf galaxies. It's the same stuff that's in the clusters and filaments, just less of it."

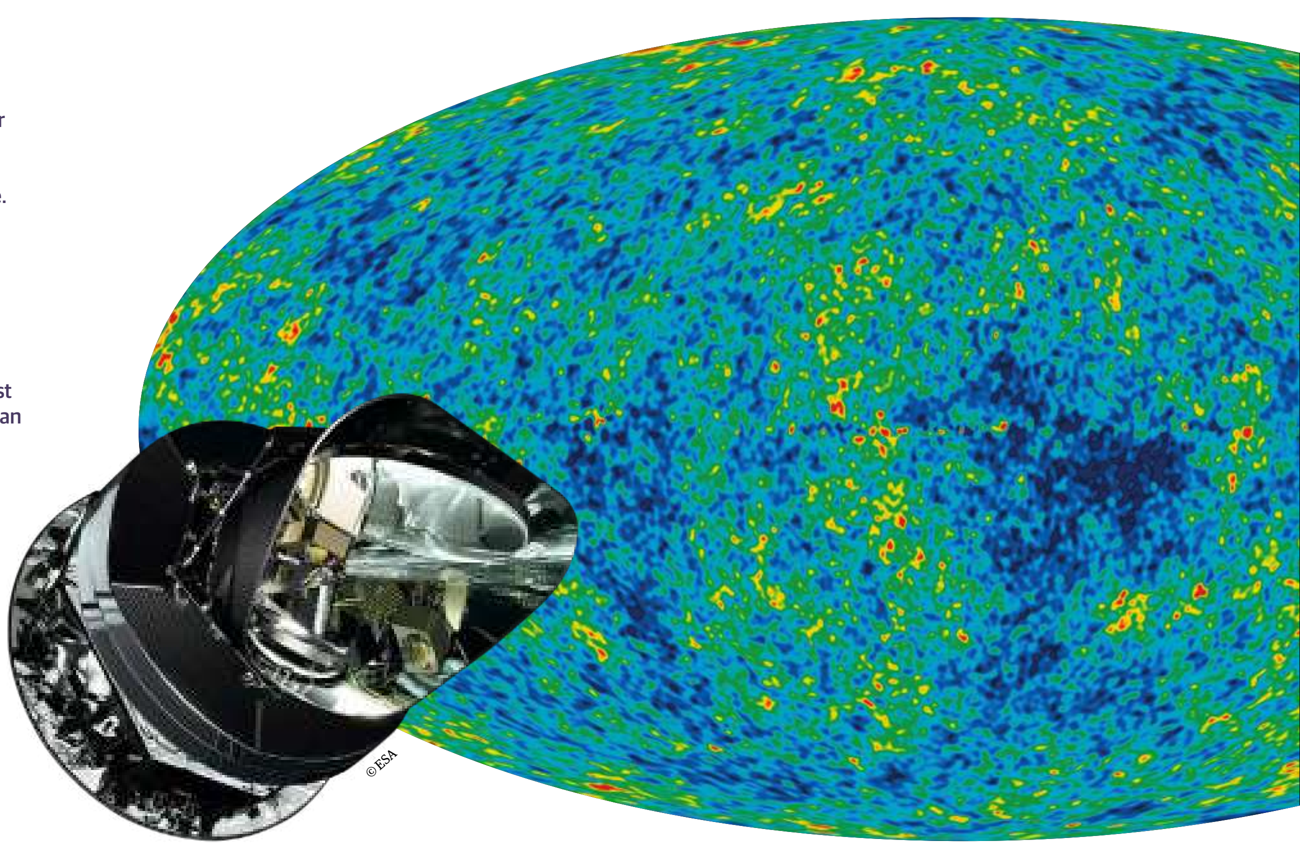
One person who studies galaxy formation in voids is Professor Rien van de Weygaert of Groningen University in the Netherlands. "The mass available to protogalaxies in voids is far less than in more moderate cosmic environments like filaments," he says. "Voids are low density, and mass is continuously streaming out. The mass clumps in voids not only start out lower mass, but are also not able to accrete much during their evolution." This is borne out of simulations Weygaert has conducted with numerous colleagues. "Because of the lower mass available to the void galaxies, the gravitational contraction and collapse of these objects proceeds more slowly." The team is studying the star formation history of these void galaxies, allowing researchers to have a better understanding of their assembly, which in turn will provide direct information on the cosmological background.

But how did voids themselves form? The best theory involves quantum fluctuations during the Big Bang growing enormously during a rapid expansion event called inflation. 380,000 years later, the universe switched from being a hot, dense plasma of subatomic particles to a transparent universe of atoms – an event known as recombination. That's because as the universe expanded it became less dense, allowing the particles to form atoms. This 'froze' into place any density fluctuations that had originated during the Big Bang. As the universe continued expanding, areas of high density became sites of galaxy formation, while low-density areas saw minimal formation, becoming voids. Boötes is thought to be composed from smaller voids, otherwise it couldn't have attained its size in the time that it did. So does this mean there are other voids?

"There are actually many voids; the universe is really empty," says Dr David Alonso of Oxford University. In fact, voids account for 70 per cent of the observable universe's volume. Alonso and his colleagues studied a particular phenomenon using data from the Sloan Digital Sky Survey's (SDSS) Baryon Oscillation Spectroscopic Survey (BOSS) and the European Space Agency's (ESA) Planck telescope. BOSS mapped the distributions of red galaxies and quasars. The Planck telescope was a space-borne observatory that mapped the relic radiation from the recombination era, which the expansion of space has stretched over 13.769

**Below:** The Planck space telescope mapped the background radiation of the universe, essential for understanding cosmic voids

**Below main:** The CMB provided the blueprint for the universe's large-scale structure, including galaxy clusters and voids



# WHAT'S HAPPENING AT THE BOÖTES VOID?

This large, relatively empty expanse was hiding in plain sight

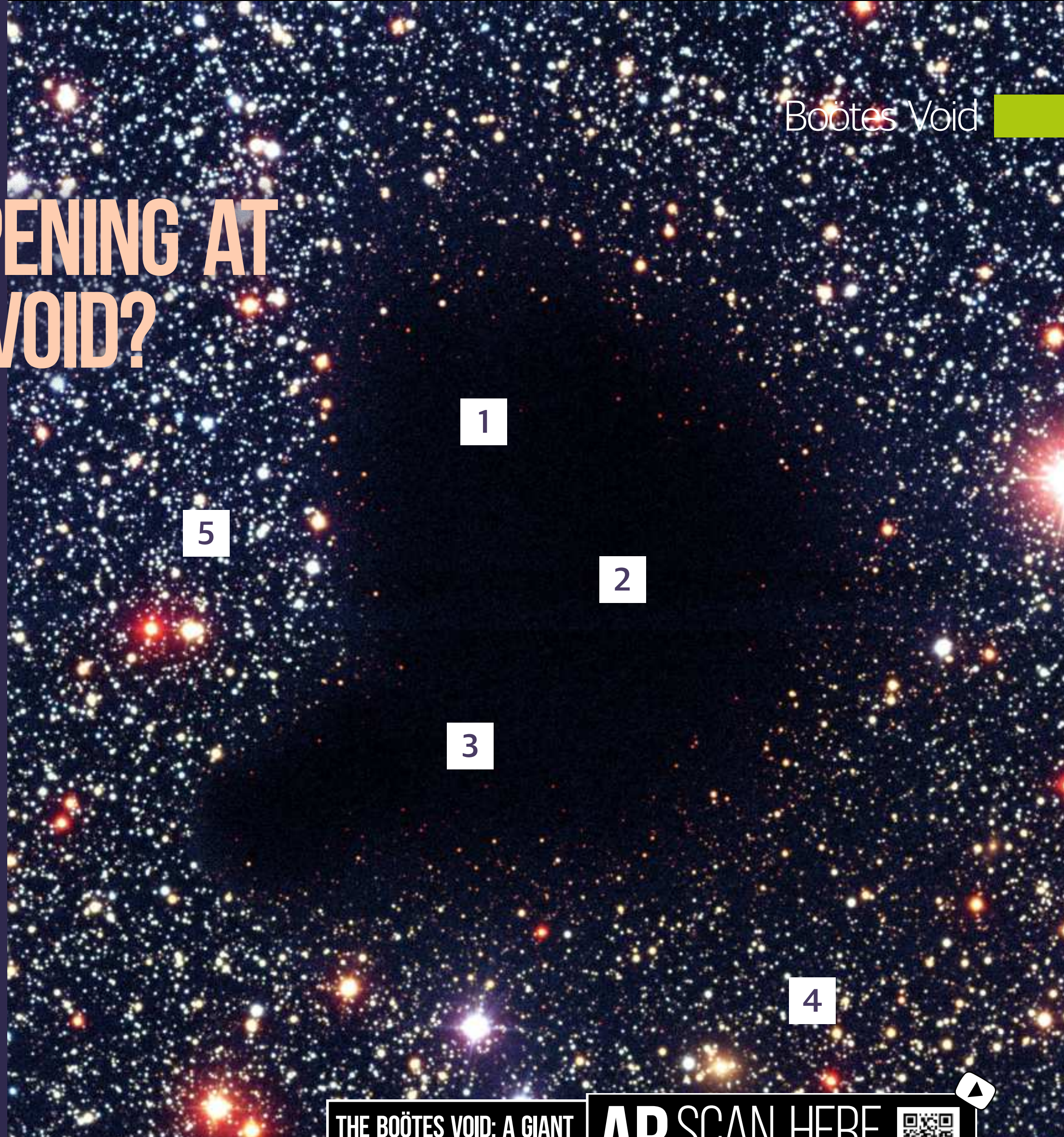
**1 Voids grew from seeds**
Quantum fluctuations from the Big Bang expanded with the universe to create voids.

**2 Smaller voids coalesced**
It's believed that smaller voids combined to form the 330 million light year-diameter Boötes 'supervoid'.

**3 Dark energy dominates**
Dark energy plays a significant role in shaping and maintaining voids such as Boötes.

**4 Dark matter attracts**
Areas of dark matter, denser than in voids, attracted more normal matter to them.

**5 Galaxy factories**
Gravity caused the matter in denser areas to collapse into observable galaxies and clusters.

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THE BOÖTES VOID: A GIANT HOLE IN THE UNIVERSE

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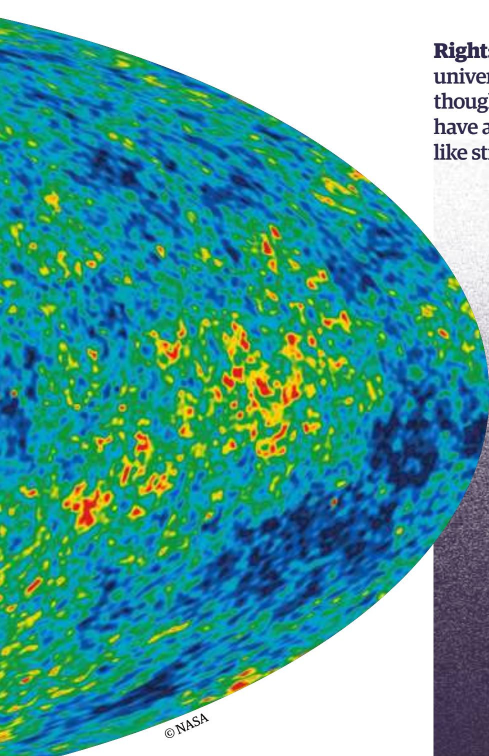

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**Right:** The universe is thought to have a web-like structure

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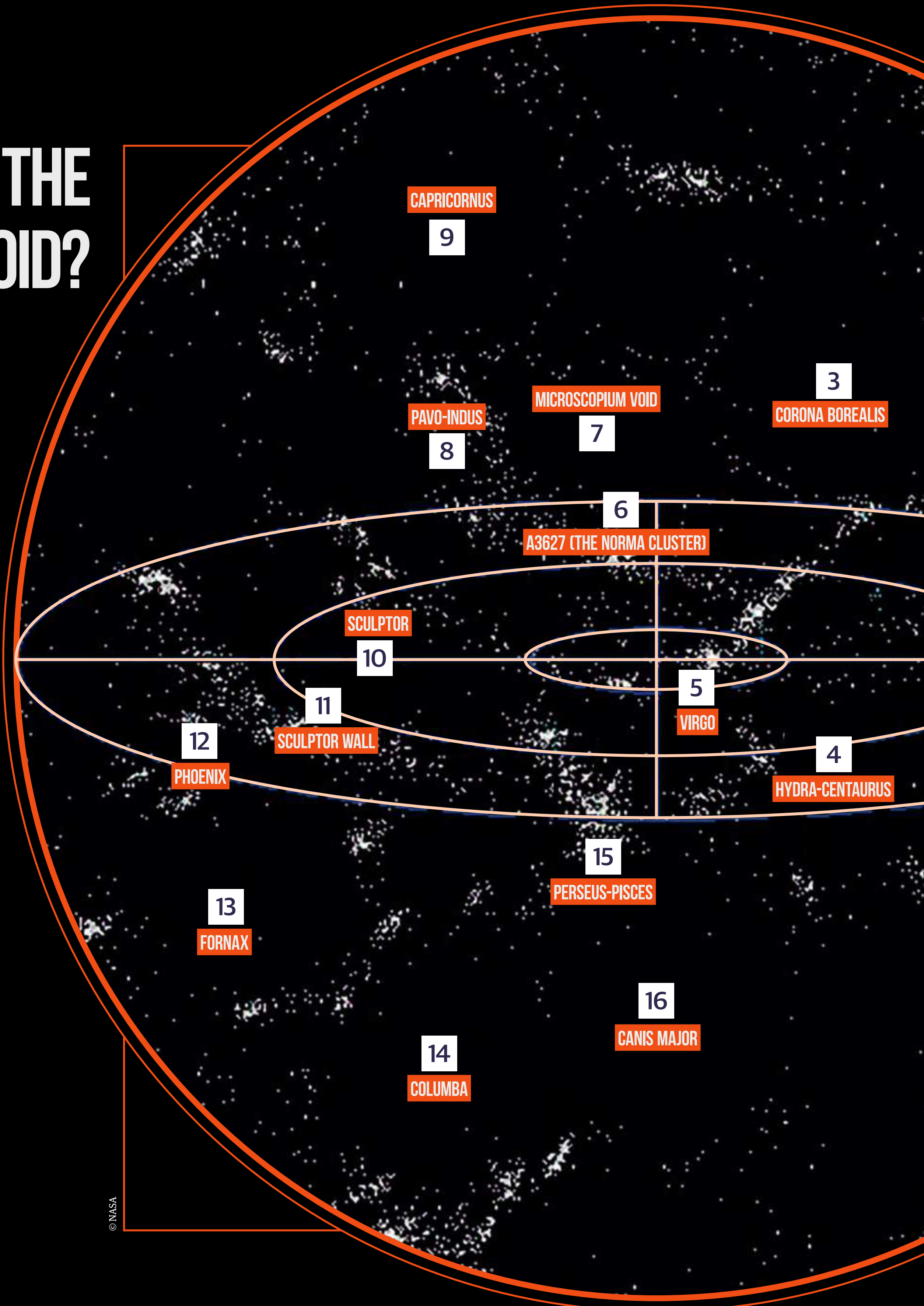
billion years into the microwave region, hence its name: the cosmic microwave background (CMB).

Alonso's team used the BOSS data to identify and map 774 cosmic voids. These were all in the Southern Hemisphere, so Boötes wasn't included. They then stacked them onto Planck's CMB data. They were studying the Sunyaev-Zel'dovich effect, where photons of the CMB are boosted by high-energy electrons in galaxy clusters. This causes distortions in the CMB that reveal the locations of clusters and voids. They compared the energy of the observed CMB photons from voids to those of modelled values. "We figured out that we can use voids to measure the mean gas pressure as long as they're sufficiently 'empty'," says Alonso.

There are hints that the void gas is slightly warmer than expected. "The most likely causes are either a statistical fluctuation in the data, or small errors in the model used to describe the gas pressure in voids," says Alonso, but he points out that the data is tentative. Another explanation is that powerful cosmic jets from supermassive black holes could be injecting energy into space, which then shows up as a slight overtemperature in void gas. The mystery could be solved soon. Alonso says that the Atacama Cosmology Telescope or the Simons Observatory should obtain cleaner CMB mapping data that could then be combined with future galaxy surveys, like that of DESI, the Dark Energy Spectroscopic Instrument.

Much of the action in the universe seems to be in galaxy clusters, superclusters and filaments, so why go to voids for answers at all? "Voids are the ultimate time capsule for the universe," says Sutter. "Unlike clusters and filaments, they've barely changed over the course of billions of years. They've preserved a memory of the early universe, and by looking at voids we can see what it was like back then." In effect, voids are pristine archaeological sites for cosmologists wanting to

# WHERE IS THE BOÖTES VOID?




© NASA

### Boötes Void

**Size:** 330 million light years

**Object type:** Cosmic void

1 The void's centre lies 700 million light years away from Earth. It was discovered in 1981, and the Hercules Supercluster forms one edge.

### Coma

**Size:** 20 million light years

**Object type:** Supercluster

2 In Coma Berenices lies this supercluster containing over 3,000 galaxies. It's the central component of the Coma Great Wall and is also part of the Coma Filament.

### Corona Borealis

**Size:** 150 million light years

**Object type:** Cosmic void

3 This void lies next to the Microscopium Void and is surrounded by the Ophiuchus, Hercules and Centaurus superclusters. It is next to the Coma Great Wall.

### Hydra-Centaurus

**Size:** 250 million light years

**Object type:** Supercluster

4 A twin-lobed supercluster that's 150 million light years away at its closest. It is the nearest such structure to our home supercluster of Virgo.

### Virgo

**Size:** 110 million light years

**Object type:** Supercluster

5 The supercluster in which we reside contains the Local Group of galaxies, of which we are a part. Virgo is 110 million light years in size with a mass of 1.48 x $10^{15}$ solar masses.

### A3627 (the Norma cluster)

**Size:** Unknown

**Object type:** Supercluster

6 220 million light years away, Norma is largely obscured behind a region of the Milky Way called the Zone of Avoidance.

### Microscopium Void

**Size:** Unknown

**Object type:** Cosmic void

7 A roughly rectangular-shaped region of space near the Corona Borealis Void and the Capricornus Void, it lies above the Norma Supercluster.

### Pavo-Indus

**Size:** Unknown

**Object type:** Supercluster

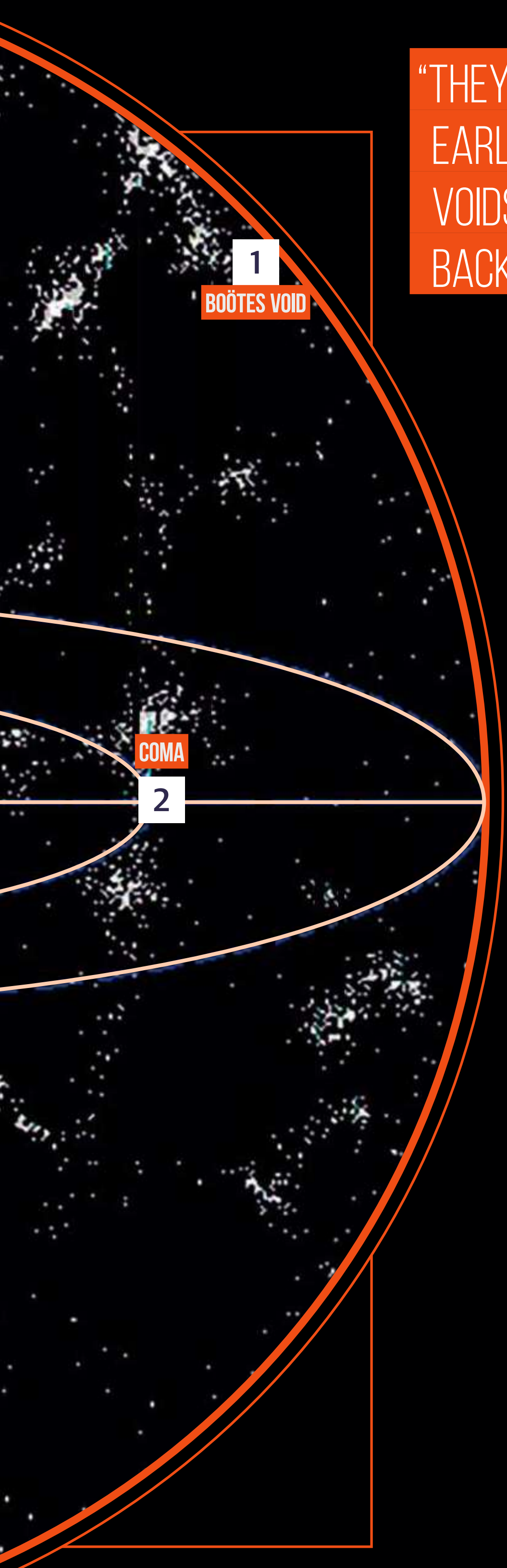
8 Located 196 million light years away, Pavo-Indus is a lobe of the much larger Laniakea Supercluster, which was discovered in 2014.

### Capricornus

**Size:** 230 million light years

**Object type:** Cosmic void

9 A 230 million light year-wide void in the Capricornus constellation, making it one of the biggest ever known, but is smaller than Boötes.




"THEY'VE PRESERVED A MEMORY OF THE EARLY UNIVERSE, AND BY LOOKING AT VOIDS WE CAN SEE WHAT IT WAS LIKE BACK THEN" PAUL M. SUTTER

### Canis Major

**Size:** Unknown

**Object type:** Cosmic void

**16** This lies next to the Perseus-Pisces Supercluster on one side and close to the Hydra lobe of the Hydra-Centaurus Supercluster on the other.

### Perseus-Pisces

**Size:** Unknown

**Object type:** Supercluster

**15** A supercluster lying 250 million light years away, it also forms part of the 1 billion light year-long Perseus-Pisces Filament of galaxies.

### Columba

**Size:** 150 million light years

**Object type:** Cosmic void

**14** Similar in size to the Corona Borealis Void, Columba lies between the Fornax and Canis Major voids. The associated constellation lies between Caelum, Canis Major and Puppis.

### Fornax

**Size:** Unknown

**Object type:** Cosmic void

**13** This roughly spherical void lies beyond the Sculptor Wall and next to the Columba Void, with only a thin stream of galaxies separating them.

### Phoenix

**Size:** Unknown

**Object type:** Supercluster

**12** Part of the Sculptor Wall, this lies next to the Sculptor Void in the Phoenix constellation. The Phoenix Supercluster is 400 million light years from Earth.

### Sculptor Wall

**Size:** 326 million light years

**Object type:** Supercluster

**11** Also called the Sculptor Supercluster and the Southern Great Wall, it measures 326 by 228 by 33 million light years and is one of a handful of cosmic 'wall' structures.

### Sculptor

**Size:** Unknown

**Object type:** Cosmic void

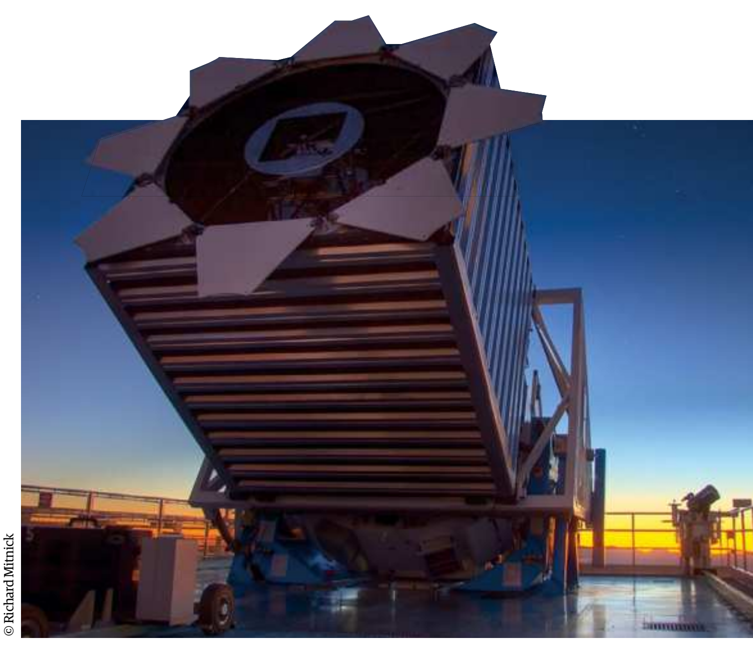
**10** Many objects in the universe are named after Sculptor. This void is separated from the supposed Eridanus Void by a sheet of galaxies and lies next to the Sculptor Wall.

know about the evolution of the universe. Voids could help uncover one of the biggest mysteries in cosmology. "Voids are the only places that are dominated by dark energy, the mysterious force that is accelerating the expansion of the universe. By looking at how they evolve, we can gain clues to understanding how this acceleration works," says Sutter. He himself was part of a team that probed dark energy by counting voids.

By studying dark energy in this way, you can test models of the Big Bang. The currently accepted model for our universe is called LCDM, or Lambda cold dark matter. As Weygaert says: "The LCDM is a hierarchical model of the build-up of structure. The first objects to form have small masses. These subsequently merge into ever larger masses. When we look at the abundance of low-mass objects that results from this process and compare it to the large objects, we see a strong divergence towards lower masses. There are far more low-mass than high-mass galaxies."

Pauline Vielzeuf of the International School of Advanced Studies, Italy, and Andras Kovács of the Instituto de Astrofísica de Canarias led a large international team to look for gravitational lensing signals in voids. Gravitational lensing, a consequence of Einstein's general theory of relativity, states that energy and mass can gravitationally bend the path of a photon in the vicinity, like a lens. The team identified voids using the Dark Energy Survey (DES) – which like BOSS mapped the southern sky – and stacked lensing maps from the Planck telescope on top. But getting good observational data is challenging, so they used supercomputer simulations to optimise and calibrate the measurements. The emergent shape and amplitude of the void lensing signal then gave them a roadmap for real-world measurements. They found that "the lensing effect of voids was strongest

**Below:** The SDSS created a 3D map of galaxy clusters and voids in the universe



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# OTHER VOIDS IN THE UNIVERSE

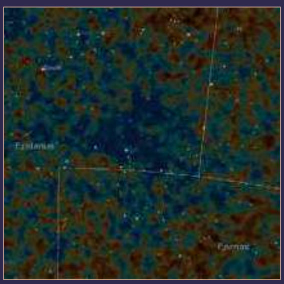
### KBC Void
At 2 billion light years in diameter, this colossal expanse is the largest void in the observable universe, representing 2.7 per cent of its size.


Source: Wikipedia commons © Pablo Carlos Budassi

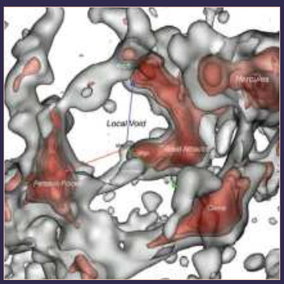
### Giant Void
It's 1.3 billion light years in diameter. The Giant Void lies 1.5 billion light years away in the constellation of Canes Venatici, but contains 17 galaxy clusters.


Source: Wikipedia commons © Pablo Carlos Budassi

### Eridanus Supervoid
An unconfirmed supervoid up to a billion light years in size, the supervoid tries to explain the existence of the 'CMB cold spot', an unusually cold area in CMB data.


Source: Wikipedia commons © Piquito veloz

### Local Void
Adjacent to the Local Group of galaxies – to which the Milky Way belongs – is the Local Void, whose size is unclear. It's at least 150 million light years in diameter.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### Southern Local Supervoid
Next to the Virgo Supercluster is the 365 million light year-wide Southern Local Supervoid. Its centre lies 313 million light years away.


Source: Wikipedia commons © Pablo Carlos Budassi

in the interior, where there are very few galaxies compared to a cosmic mean density". This signal then progressively faded towards the edges before changing in areas where there were high galaxy densities. "A positive lensing effect is expected in a surrounding ring where galaxies evacuated from voids reside. These characteristic features in the lensing profile helped us to estimate the amplitude and shape of the signal from DES data in comparison to simulations," they wrote.

What does this result tell us about void environments? Here the differences between dark matter and dark energy become important. Dark matter, an invisible form of mass whose nature is as yet unknown, is only detectable via its gravity and clumps around galaxy clusters. The even more mysterious dark energy accelerates the universe's expansion, but doesn't clump. This, says Kovács, is the key advantage of voids. "The [LCDM] model of dark energy is completely featureless in space and also does not change with time." This mirrors Sutter's comments about voids being the best place to observe dark energy directly due to the paucity of both dark and visible matter inside.

There was another reason for the study, as Vielzeuf and Kovács explain: "A key motivation for our DES analysis was that the largest cosmic voids have shown stronger-than-expected imprints in CMB temperature maps, which challenges the standard cosmological model and may indicate the need for alternative explanations." Some of these alternatives may include modified gravity models. As they point out, the data for their latest study doesn't show this, but still hints at some mystery. "The lensing signals we measured were consistent with the Standard Model, which narrows down the sources of the anomalous imprints, but does not explain them."

Further work is required. "More data is necessary to accurately study different subsets of voids by radius, or understanding the possible evolution of the lensing signal with redshift. To this end, we continue working with the DES team to analyse a new dataset," say the pair. They have a PhD student working with them on these analyses, using three times as much data as before and comparing different possible definitions of cosmic voids. "They are part of the Euclid Consortium and participate in modelling the expected lensing signals from more distant voids." Euclid, scheduled for launch in 2022, is a space-borne ESA spacecraft designed to study the expansion of the universe.

Could such techniques be applied to voids like Boötes? Here the pair are cautious. "While there is growing interest in investigating the lensing effect of deep voids as well as dense clusters, such measurements are truly challenging due to the significant noise levels." For their analysis their team used hundreds of voids to statistically analyse the CMB lensing maps, and a strong signal eventually emerged. vv

A study of Boötes would have to include a large set of Northern Hemisphere voids, something that's almost certain to happen in the future. Sutter, Weygaert and others plan follow-up work with the Vera Rubin Telescope, Euclid, NASA's Nancy Grace Roman Space Telescope, due for launch in 2025, and the Square Kilometre Array. As Sutter says: "There's a lot more to learn about voids!"

HOW DO COSMIC SUPERVOIDS PROVE THAT DARK ENERGY EXISTS?

AR SCAN HERE


Source: Wikipedia Commons © Pablo Carlos Budassi

**Left:** Boötes is one of the largest and best known cosmic voids

**Kulvinder Singh Chadha**
*Space science writer*
Kulvinder is a freelance science writer, outreach worker and former assistant editor of *Astronomy Now*. He holds a degree in astrophysics.

# A WEIRD WORLD AROUND A WARPED STAR

## The spacecraft CHEOPS has categorised a strange new exoplanet with an odd orbit

Europe's new telescope studying alien planets has created its first detailed portrait of a world, and it's a weird one: searingly hot, and tilted around a warped star.

The European Space Agency (ESA) launched the CHaracterising ExOPlanets Satellite, nicknamed CHEOPS, in December 2019; the spacecraft began science observations in the following April. CHEOPS isn't designed to discover alien planets, but rather to inform scientists about known ones, so that they can construct portraits of the worlds. In the mission's first results, scientists on the CHEOPS mission have done just that, forming a detailed picture of the planet WASP-189b, which was first detected in 2018. "This first result from CHEOPS is hugely exciting," Kate Isaak, project scientist for CHEOPS at the ESA, said. "It is early definitive evidence that the mission is living up to its promise in terms of precision and performance."

The CHEOPS observations suggest that WASP-189b is a strange world orbiting a strange star. Scientists had a hunch that might be the case, which is why mission scientists chose to study the planet so early in the spacecraft's tenure. The star is super-hot - so hot it looks blue - and the planet is so close to the star it orbits in just 2.7 Earth days. "Only a handful of planets are known to exist around stars this hot, and this system is by far the brightest," Monika Lendl, an astrophysicist at the University of Geneva in Switzerland and lead scientist, said. "WASP-189b is also the brightest hot Jupiter that we can observe as it passes in front of or behind its star, making the whole system really intriguing."

Observing a planet passing in front of its star is, at this point, fairly commonplace - the so-called transit technique is how NASA's venerable Kepler Space Telescope and its successor, the Transiting Exoplanet Survey Satellite (TESS), spot planets blocking light as they pass in front of stars. Watching a planet pass behind its star is much more difficult, but WASP-189b is so bright that scientists can do just that. "Because the exoplanet WASP-189b is so close to its star, its dayside is so bright that we can even measure the 'missing' light when the planet passes behind its star," Lendl said. "It appears that the planet does not reflect a lot of starlight. Instead most of the starlight gets absorbed by the planet, heating it up and making it shine."

CHEOPS studied WASP-189b in March, April and June 2020, catching the planet passing behind its star four times and in front of the star twice. From that data, scientists calculated some key features of the system. First the researchers determined that the planet is pretty toasty at about 3,200 degrees Celsius (5,800 degrees Fahrenheit) - so hot that even iron would turn to gas. The scientists also calculated the planet's size: about 1.6 times the radius of Jupiter.

The new CHEOPS observations also told scientists more about WASP-189b's star. "We also saw that the star itself is interesting - it's not perfectly round, but larger and cooler at its equator than at the poles, making the poles of the star appear brighter," Lendl said. "It's spinning around so fast that it's being pulled outwards at its equator!"

Unlike in our Solar System, where planets orbit around the Sun's equator, WASP-189b orbits its star at a dramatic tilt, bringing it close to the star's poles. That odd characteristic makes scientists suspect that the planet could have formed much farther away from the star, then some powerful gravitational force - perhaps another star - kicked the planet inward and askew. The CHEOPS scientists say that this sort of work is precisely what the telescope was designed to do: take a known exoplanet and give scientists a much more detailed view of that world than a passing shadow. "CHEOPS will not only deepen our understanding of exoplanets," Isaak said, "but also that of our own planet, Solar System, and the wider cosmic environment." Wasp-189b's odd nature did just that.

**Below:** Artist's impression of hot Jupiter WASP-189b

"ONLY A HANDFUL OF PLANETS ARE KNOWN TO EXIST AROUND STARS THIS HOT, AND THIS SYSTEM IS BY FAR THE BRIGHTEST"

MONIKA LENDL

ALIEN WORLDS IN FARAWAY GALAXIES

# EXTRAGALACTIC PLANETS

**The search for alien worlds continues, with surprising consequences**

Reported by Colin Stuart

© Tobias Roetsch

We should count ourselves lucky. For thousands of years humans have gazed up at the night sky, wondering whether or not we are alone. We are among the first generations to know for sure that our Solar System is just one of many strung out across the vast cosmos. Our discovery of around 4,000 alien worlds dancing around distant stars – known as exoplanets – over the last three decades has quite rightly been lauded. It's a wonderful achievement that helps put us in our astronomical place. The haul has thrown up a zoo of exciting and enchanting worlds, from those that dance around two suns to planets with diamond rain, bubbling metal lava and possibly even liquid water.

## WHERE HAVE WE DISCOVERED EXTRAGALACTIC PLANETS?


Source: Wikipedia Comons© Adam Evans

### ANDROMEDA

**Potential planets:** One

**What do we know?** It's six times the mass of Jupiter

Our nearest major galaxy, Andromeda sits 2.5 million light years from us. Its relative proximity means it represents one of our best shots at finding extragalactic exoplanets. It's home to at least double the number of stars found in the Milky Way.


© NASA

### RXJ1131-1231

**Potential planets:** Trillions

**What do we know?** They range in mass, from the Moon up to Jupiter

This galaxy is lensing the light from a distant quasar sitting around 6 billion light years from Earth. It has a central supermassive black hole that tips the scales at 130 million solar masses.


© NASA/ESA & Hubble

### M51

**Potential planets:** One

**What do we know?** Similar in size to Saturn and orbiting at least as far out as Uranus and Neptune

This galaxy is accompanied by a dwarf galaxy that has interacted with its host in the past. It sits ten-times further away than Andromeda and is less than half as wide as our Milky Way.

Despite the accolades, these discoveries are rarely put into their true context. It is easy to forget just how much of the universe's real estate remains unexplored. All of the confirmed planets found to date reside in our own Milky Way galaxy, and in our tiny corner of it to boot. There are around 2 trillion other galaxies in the observable universe. To see how much we've poked around in so far, imagine that this hoard of galaxies is represented by the total land area of the Earth. On that scale, our Milky Way accounts for the space taken up by the average UK bungalow. The area that includes the thousands of exoplanets we've found so far is smaller than a sock drawer in the spare bedroom.

It's no surprise that astronomers would love to know more about planets beyond our current horizons, and those outside the confines of our own galaxy in particular. "They are so unimaginably far away that we're unlikely to ever be able to reach them, but knowing about extragalactic planets is still really useful," says Lewis Dartnell, an astrobiologist at the University of Westminster. "They help build up the stats we have on the wonderful diversity of different worlds that exist."

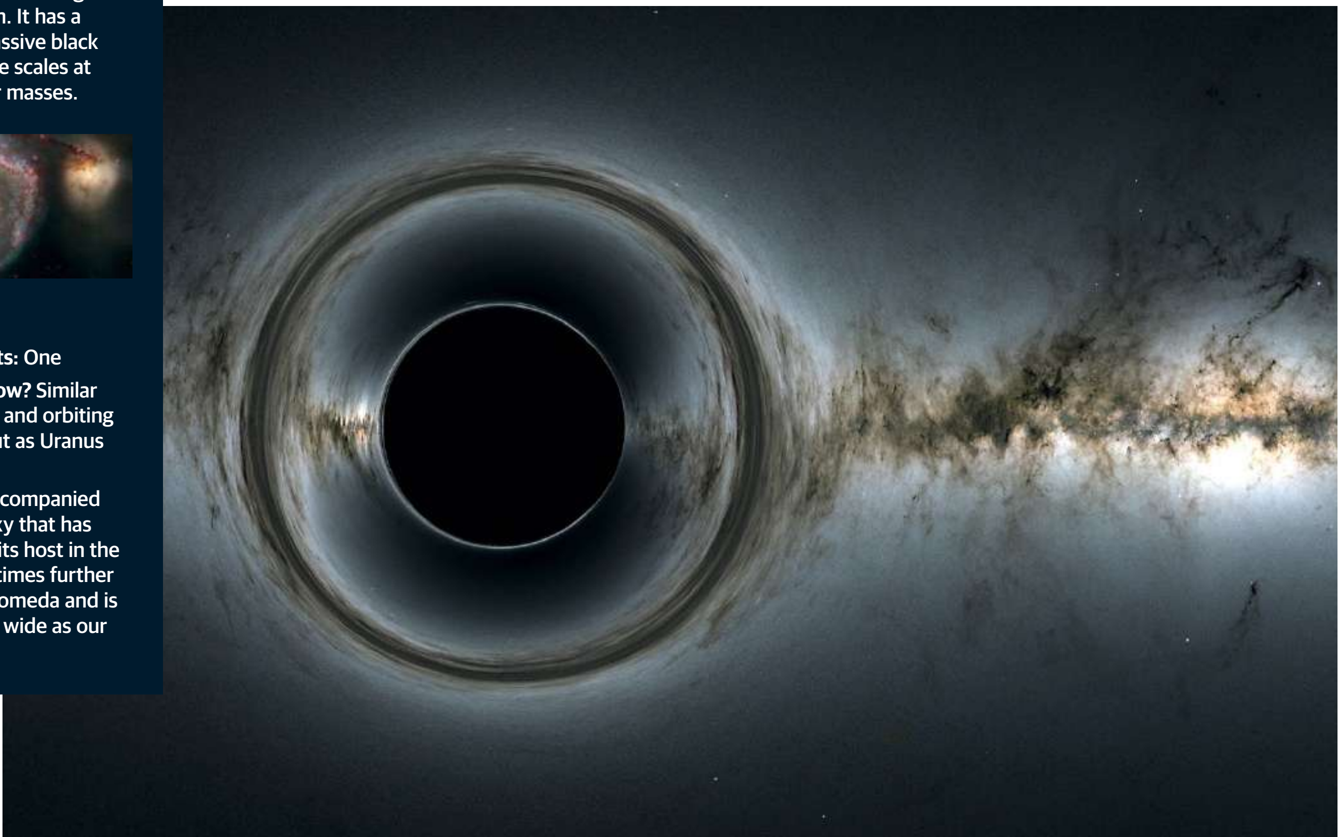
There's every reason to suspect that they are out there. After all, a huge part of our understanding of space hinges on the fact that there's nothing special about the part of space we occupy. This so-called Copernican principle – named after the Polish mathematician and astronomer Nicolaus Copernicus – tells us that if there are planets here, there should be planets everywhere. However, as Dartnell says, the distances involved are intimidating. Spotting an Earth-sized planet in the Milky Way is hard enough – it's the same as trying to see an ant on the Moon. Seeing one in our nearest major galaxy, Andromeda, is a whole new ball game. It's the equivalent of being able to see a virus on the lunar surface. To photograph one we'd need a telescope a hundred-times wider than the entire Earth. With that clearly out of the question for the foreseeable future, the big question is whether there are other ways to find them.

Back in 2010 astronomers thought they had discovered an extragalactic exoplanet, albeit one that now resides in the Milky Way. The planet, HIP 13044 b, was found orbiting a star in a region of our galaxy called the Helmi stream. It's the remnant of a dwarf galaxy that was swallowed by our Milky Way between 6 and 9 billion years ago, meaning the planet likely formed outside of our galaxy before being consumed into it. However, follow-up work concluded that the planet probably doesn't exist and was a figment of incorrect data analysis.

A year before that discovery, another team of astronomers claimed to have teased out

> "THEY ARE SO UNIMAGINABLY FAR AWAY THAT WE'RE UNLIKELY TO EVER BE ABLE TO REACH THEM" LEWIS DARTNELL

**Below:** Some of the potential exoplanets could actually be miniscule black holes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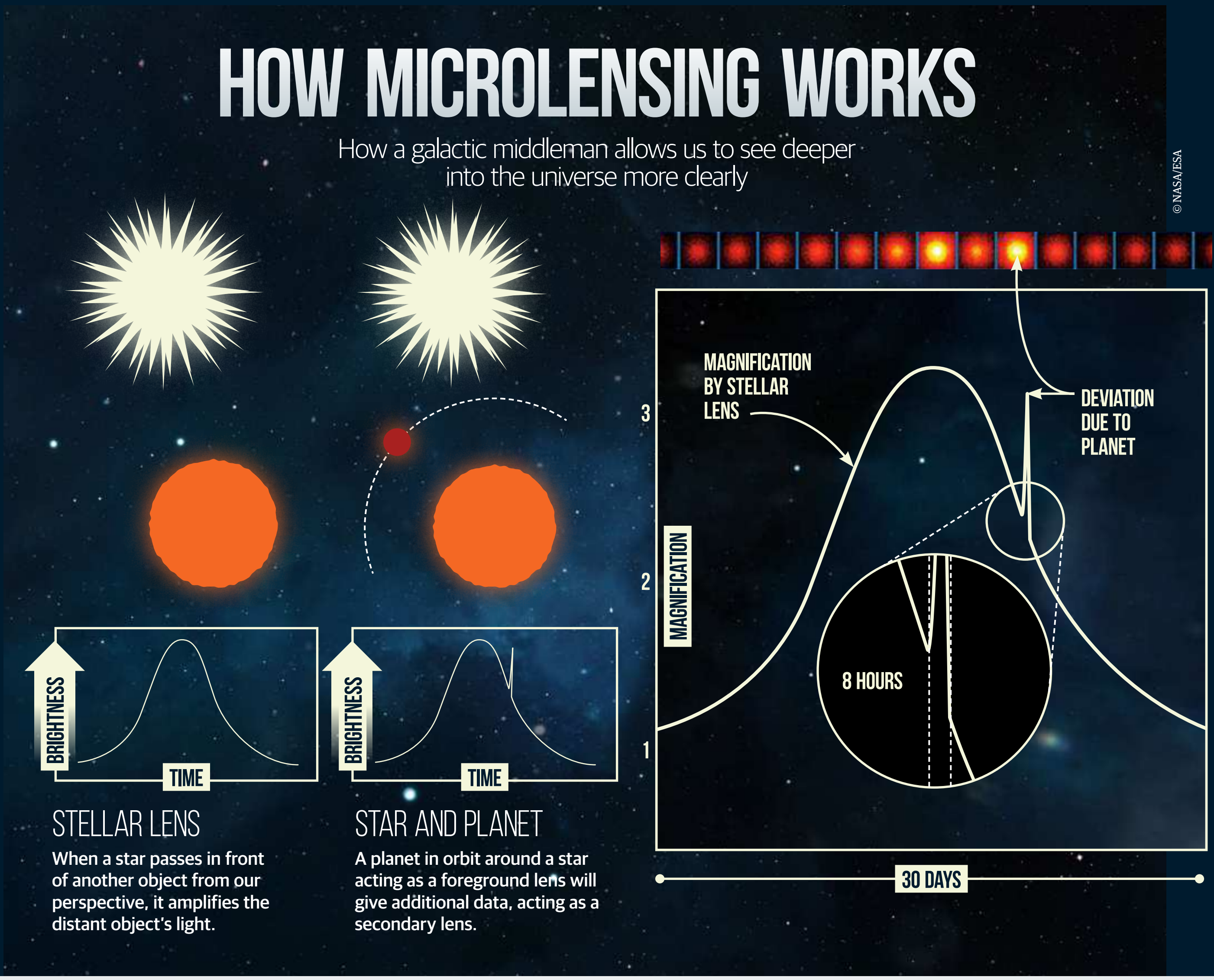



the presence of an extragalactic exoplanet in Andromeda. Their find relied on a technique called gravitational microlensing. Massive objects warp the space around them. Earth, for example, is caught in the distorted space created by the presence of the Sun, just as the Moon is caught in the distorted space created by the Earth. This warping of space can act like a lens, magnifying light from a background object as it makes its way around a massive object like a star or galaxy on the long trek to Earth. You can see a similar effect if you look at an object through the curved base of a wine glass. Astronomers can glean some details of the object acting as a lens from the exact way the background light gets magnified.

When astronomers looked at a star acting as a lens in Andromeda, there appeared to be more lensing than the star alone could provide. They concluded that the star was accompanied by a planet six times the mass of Jupiter, and this was adding a little extra lensing. However, that's all we can say about it. "The way that these planets are discovered means we're unable to do any follow-on studies," Dartnell says. Each lensing event is a one-off, as it relies on an exact alignment between a foreground lens and background object. This geometry is unlikely to be repeated again, and so we are unable to probe the system further or check to see if the planet is really there at all.

In 2018 there came a slightly different approach. A team of astronomers led by Xinyu Dai from the University of Oklahoma may have found trillions of extragalactic exoplanets in one fell swoop. This time they were looking at an entire galaxy some 3.8 billion light years away that was lensing light from an even more distant quasar. The pattern of lensing they observed could not be explained using the galaxy's stars alone. They modelled different ways to explain the discrepancy, settling on the presence of a huge number of unseen objects ranging in mass from the Moon all the way up to Jupiter.

"They could be free-floating planets," Dai says. Also known as 'rogue' planets, they are worlds jettisoned from young solar systems as newly

**Right: Copernicus told us that there's nothing special about our place in the universe**

Source: Wikipedia Commons© Public Domian

**Right:** An extragalactic exoplanet could have been absorbed into the Milky Way

© ESA

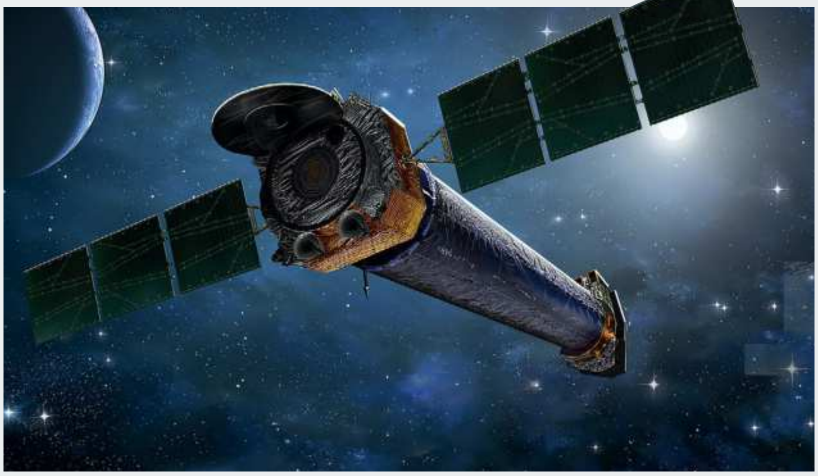
formed planets jockeyed and jostled for superiority. We've already found rogue planets wandering between the stars in our own Milky Way galaxy, so it's no surprise to find them elsewhere in the universe. According to Dai's calculations, there could be 2,000 rogue extragalactic exoplanets for each and every one of the billions of ordinary stars in this distant galaxy.

While planets may be the most obvious contender, it's not the only option they are considering. "All we can tell is the mass of these objects," says Dai's student Saloni Bhatiani. "We can't yet say anything about their size," she says. So there is a chance that they aren't planets at all, but primordial black holes instead. Black holes are normally associated with the deaths of massive stars, but many cosmologists believe that miniature versions were created not long after the Big Bang. A black hole that weighs the same as Earth would measure just one centimetre (0.3 inches) across.

Until we can work out the physical size of these objects it is hard to tell the difference between primordial black holes and rogue extragalactic exoplanets and whether the missing mass can be explained by a combination of the two. Thankfully that's not beyond the realms of possibility. "With better data we think we can constrain the properties of individual objects," says Dai. They've already seen a similar effect in two other galaxies and have three more lensing galaxies in the bank awaiting further analysis. In the meantime, we're still waiting for the first cast-iron proof of an extragalactic exoplanet.

Another team of astronomers threw a possible candidate into the ring in September 2020. Led by Rosanne Di Stefano at the Harvard-Smithsonian Center for Astrophysics, they think they've spotted an exoplanet in the Whirlpool Galaxy, Messier 51 (M51). At 30 million light years away, the galaxy is quite close to us in cosmic terms – you can see it through a telescope in the constellation of Canes Venatici, not far from the famous seven saucepan-shaped stars of the Big Dipper. The potential new planet, with the trip-off-the-tongue name of

"THEY HELP BUILD UP STATS ON THE WONDERFUL DIVERSITY OF DIFFERENT WORLDS" LEWIS DARTNELL



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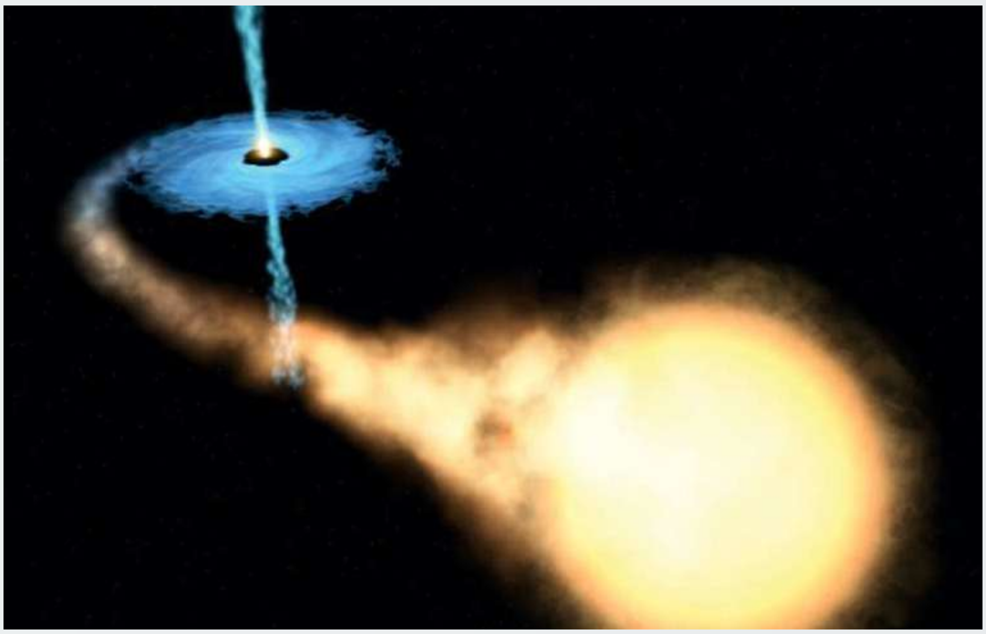
**Left:** NASA's Chandra X-ray telescope, which was used to spot an exoplanet in M51

**Below:** The potential planet found in M51 orbits an X-ray binary similar to this one



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## EXTRAGALACTIC PLANETS BY THE NUMBERS

**2010**
Year of the first possible extragalactic planet discovery

**2 TRILLION**
The number of other galaxies in which to look for planets

**4,374**
The number of exoplanets found in our own Milky Way

**1999**
The year NASA's Chandra X-ray Observatory launched

**0.12**
The size in millimetres of the smallest potential primordial black hole in RXJ1131-1231

M51-ULS-1b, is not your common or garden world, however. For starters it is in a binary system – it orbits two objects instead of one. One of those objects is a compact dead star – either a neutron star or black hole – and the other is a huge star.

The two objects are a brilliant source of X-rays, producing at least 100,000-times more X-ray energy than the Sun emits across all forms of light. Using the Chandra X-ray Observatory, Di Stefano saw the star dim for a few hours, hinting that a planet may have got in the way and temporarily blocked out our view of the X-ray light. This technique – called the transit method – is one way that we find conventional exoplanets. However, one transit isn't usually enough to be confident you've found a new world. If it really is an orbiting planet, you would expect to see subsequent transits as the planet comes round in front of the stars again. Normally it takes three transits to be confident that the variation in light you're seeing isn't being caused by something else. Perhaps the X-rays are dimming for another entirely unrelated reason.

If it does turn out to be a planet, Di Stefano's calculations suggest it would be a gas giant a little smaller than Saturn. One that orbits the binary stars at a distance tens of times further than Earth's distance from the Sun. Those characteristics alone would make it an extremely unlikely place to find liquid water and life. But the huge amount of X-ray radiation present in the system draws a line through the prospect entirely.

So far these potential extragalactic exoplanets have been discovered using some of the same techniques we use to find exoplanets in our own galaxy. However, Camilla Danielski and Nicola Tamanini believe that an exciting new technique is already in the pipeline – one that relies on gravitational waves.

First discovered in 2015, gravitational waves are ripples in the very fabric of space itself, generated by events occurring within it. The collision of two black holes, for example, sends gravitational waves soaring outwards at the speed of light. Just such an event provided the first-ever gravitational waves to be detected. They've become so commonplace now that the Laser Interferometer Gravitational-Wave Observatory (LIGO) picked up more than one event a week in 2019.

This elaborate machine works by sending laser beams down two four-kilometre (2.4-mile) arms at right angles to each other. The lasers hit mirrors at the ends of the tunnels and are reflected back to the start. As the two arms are the same length, usually the two laser beams arrive back at the same time. However, if a gravitational wave passes through, it changes the length of one of the arms and one laser arrives ahead of the other. While this may sound simple in principle, it's exceptionally subtle in practice. One arm changes in length by the width of a proton – the positively charged particle in the heart of an atomic nucleus. It's the equivalent of the 40 trillion kilometre (24 trillion mile) distance to the nearest star after the Sun changing by the width of a human hair.

Such a machine is good for picking up cataclysmic events like the collision of mighty black

## WHY DO WE THINK THERE ARE PLANETS IN OTHER GALAXIES?

We used to think that we were at the centre of everything. That the Sun, planets and stars all rotated around the Earth. The Copernican revolution changed all that, relegating us to just another planet orbiting the Sun. We realised that the stars were just distant copies of the Sun. Much of modern astronomy hinges on the idea that there's nothing special about our place in the universe. This is called the Copernican principle. This means that if there are planets here there should be planets in other galaxies too.

We also know that planets are a natural by-product of star formation – they form from the leftovers. Wherever we see stars, we also expect to see planets too. The growing field of astrochemistry has also provided evidence that other galaxies contain complex molecules required to fashion the building blocks of life. It is increasingly unlikely, it seems, that we are the only living planet in the entirety of the universe. Yet finding undeniable evidence that's really the case is a significant challenge that the next generations of astronomers will try hard to meet. Whether we are alone is perhaps the biggest question scientists can ask.

© NASA/ESA

**Opposite:** When the Sun dies it will form a planetary nebula, becoming the central white dwarf

**Below:** This upcoming mission could be used to spot planets using gravitational waves

holes, but according to Danielski and Tamanini, we need an even bigger gravitational-wave detector if we're going to use them to discover extragalactic exoplanets. "They emit gravitational waves in a different frequency range to LIGO," says Tamanini, a researcher at the Max Planck Institute for Gravitational Physics in Germany. To pick them up we need a detector with arms significantly longer than LIGO's. Fortunately such a machine is already being planned: the Laser Interferometer Space Antenna (LISA).

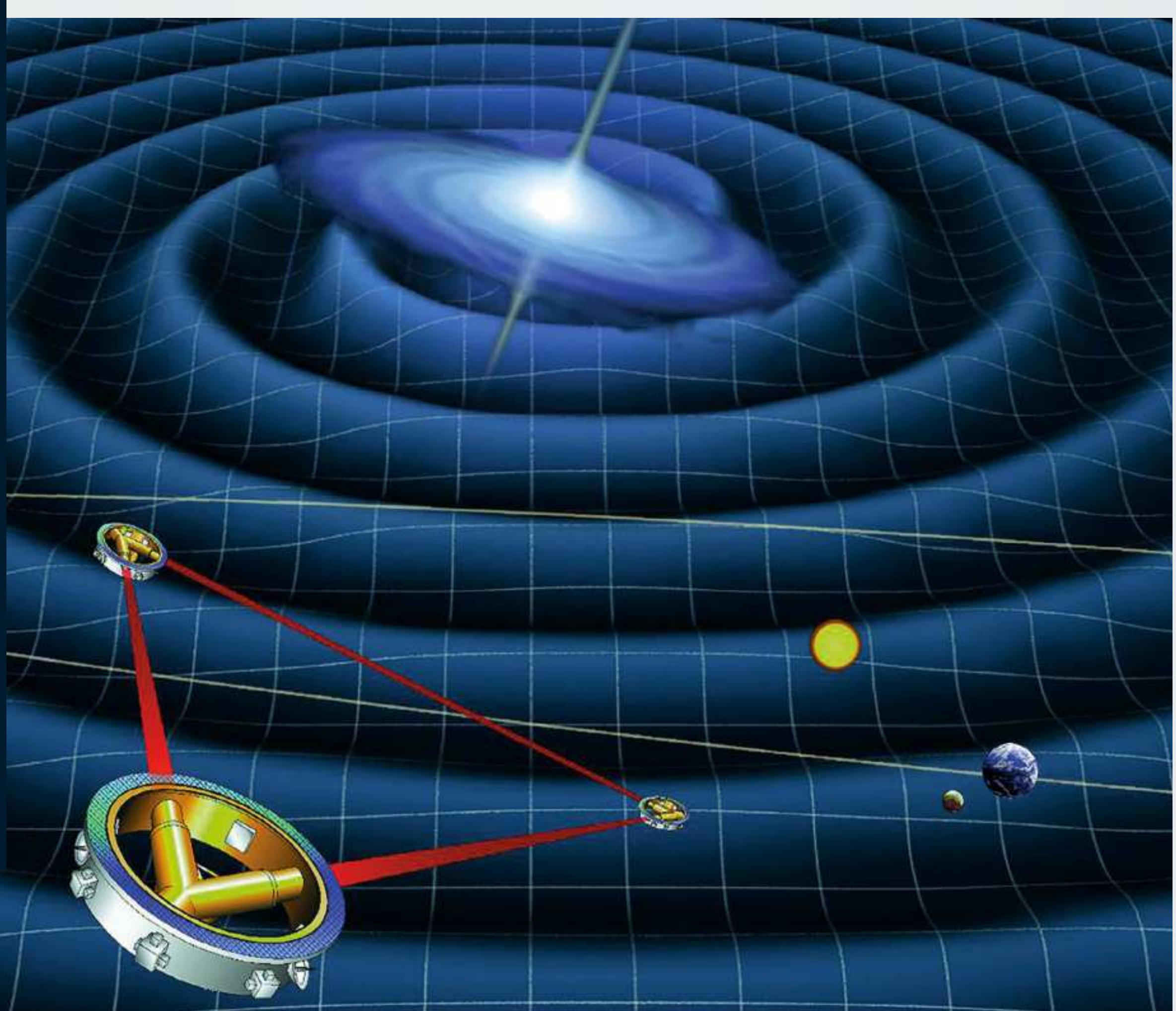
With a prospective launch date planned for 2034, LISA is a European Space Agency (ESA) mission consisting of three spacecraft flying in formation to create an equilateral triangle in space. Each side of the triangle will be 2.5 million kilometres (1.5 million miles) long. Back in 2015 the ESA successfully flew the LISA Pathfinder mission to test out the feasibility of building the full mission.

Danielski and Tamanini think LISA will be perfect for detecting planets orbiting around binary white dwarf stars. A white dwarf is the Earth-sized core of a Sun-like star after it has shed its outer layers at the end of its lifetime. Two white dwarfs orbiting each other create gravitational waves in just the same way as two conjoined black holes do. However, the presence of a planet in orbit would change things. "Its gravitational pull upsets the regularity of the waves," says Tamanini. According to their calculations, LISA will be able to pick up planets orbiting binary white dwarfs in the Magellanic Clouds – the two dwarf galaxies that orbit our Milky Way.

Not only will this tell us more about the nature of extragalactic exoplanets, it could also be a crystal ball into our own future. We know very little about what happens to planets when their stars die. "It is going to allow us to pin down the life of a planet in a phase we don't know about," says Danielski, who works at the Centre for Space Exochemistry at University College London. "We are seeing the future of our Solar System," she says. Although the Sun doesn't have a binary companion, it will turn into a white dwarf in around 7 billion years. Discovering these planets could help us understand what will happen to Earth when it does.

After all, that is what hunting down exoplanets is all about. They allow us to hold up a mirror to ourselves, giving us a clearer picture of who we are and how we fit into the rich and vibrant tapestry of the universe.

**Colin Stuart**
*Astronomer & space science writer*
Colin holds a degree in astrophysics, has written over 17 books on space and has an asteroid named in his honour: 15347 Colinstuart.



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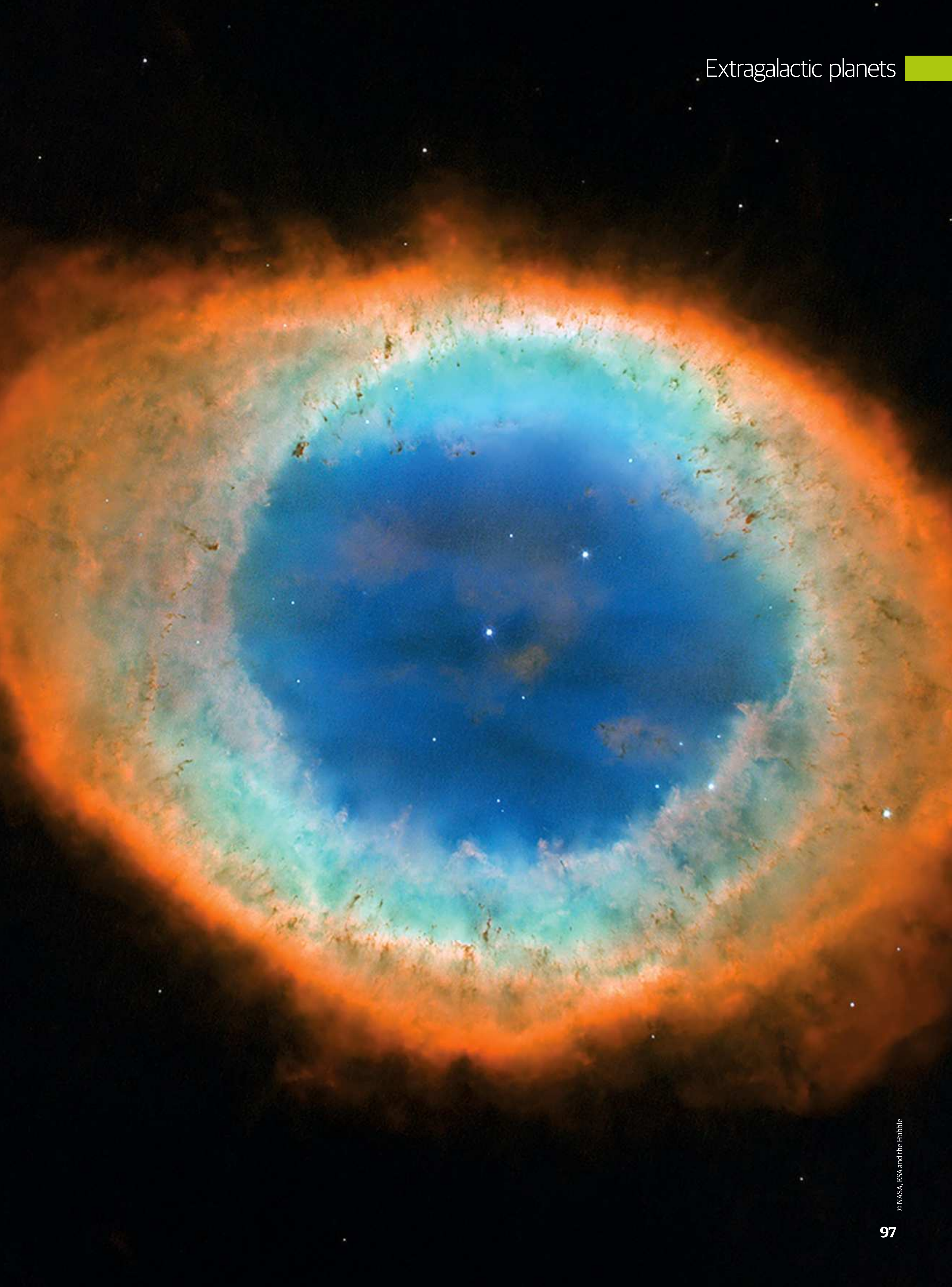


# SCIENTISTS SPOT MAGNETARS' MISSING LINK

## These magnetic stars might be more like pulsars than originally suspected

Researchers have apparently found a 'missing link' between two types of pulsars. Pulsars are fast-spinning neutron stars, the superdense, collapsed cores left over from the explosive deaths of massive stars. Pulsars emit beams of radiation from their poles that appear to pulse when they're observed from Earth, hence the name. Pulsars don't actually pulse, though – that's an effect of their rotation.

Scientists had thought that two different kinds of pulsars – magnetars, which sport extremely powerful magnetic fields, and rotation-powered pulsars – emit their beams in different ways. But a new study suggests that these extreme objects have more in common than was previously presumed. "Our study has given us new understanding of the neutron stars with high magnetic fields," said Chin-Ping Hu, a visiting researcher at the RIKEN Cluster for Pioneering Research in Japan.

On 12 March scientists discovered a new gamma-ray burst with the Burst Alert Telescope aboard NASA's Neil Gehrels Swift Observatory, a space-based gamma-ray telescope. The object, J1818.0-1607, which the researchers believe is a magnetar, immediately inspired follow-up X-ray observations with the Neutron star Interior Composition Explorer (NICER), an instrument aboard the International Space Station (ISS).

Using NICER, the researchers found that the magnetar has a pulsation period – the time between stellar pulsations – of 1.36 seconds, the shortest ever spotted in a magnetar. They also found that the magnetar is fairly young, forming just 420 years ago – from our perspective, at least. The object lies 16,000 light years from Earth, so everything astronomers are observing with the magnetar happened long ago. Strangely they also found that this magnetar's X-ray emission was lower than that of other magnetars.

Notably, the magnetar was exhibiting 'spin-down behaviour'. Because of this the team think that its emissions were at least in part powered by rotation. This is significant because typically rotation-powered pulsars are thought to be the ones that produce beams through rotating. This finding draws the two objects closer together and expands scientists' understanding of how and why these objects produce their beams. Additionally, Hu added: "Recent radio observations suggest that magnetars may be a cause of mysterious phenomena called fast radio bursts. We look forward to investigating further."

> "WE HAVE A NEW UNDERSTANDING OF THE NEUTRON STARS WITH HIGH MAGNETIC FIELDS"
>
> CHIN-PING HU

**Below:** Magnetars are dense cores of massive stars with strong magnetic fields

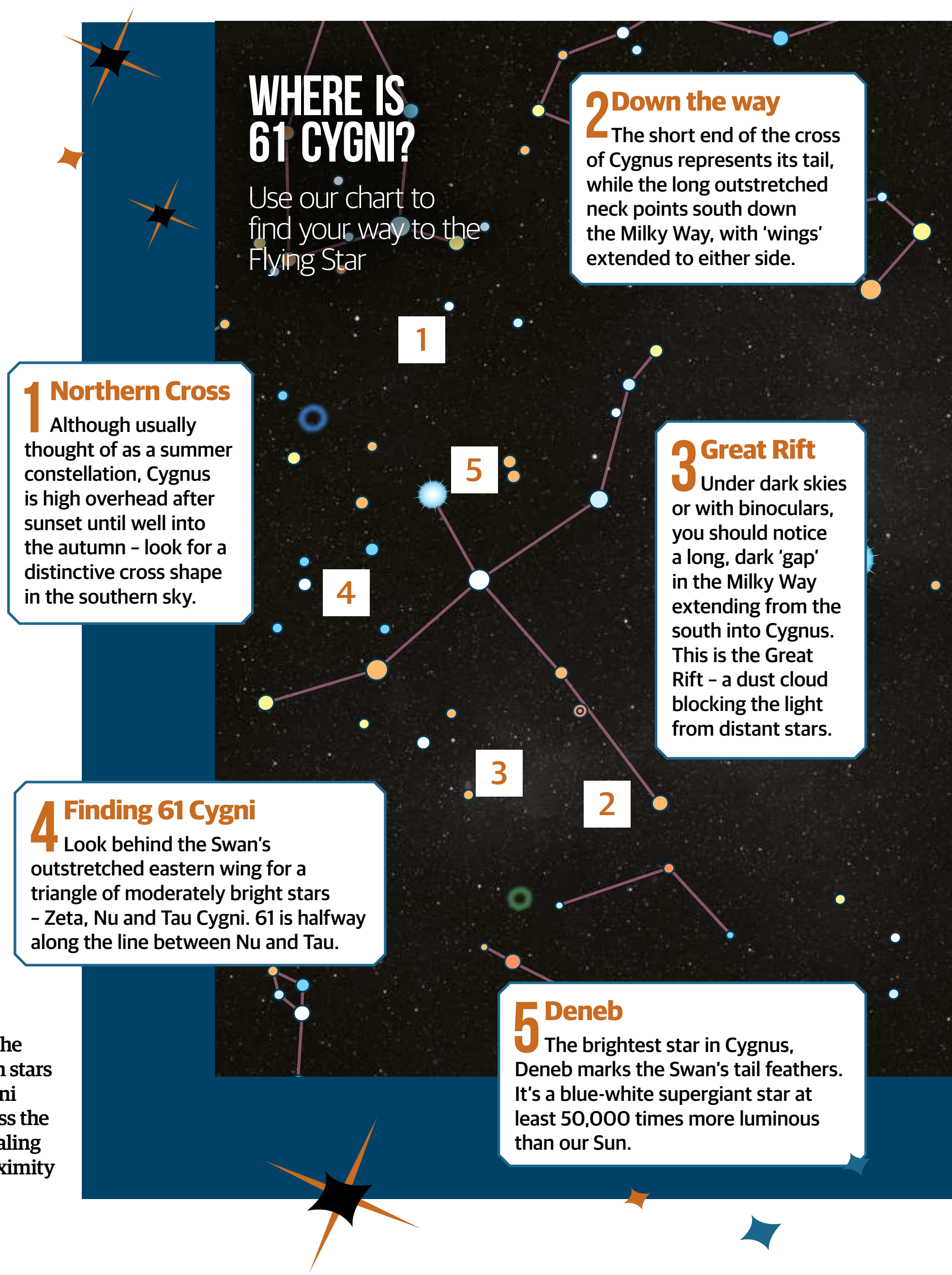
© ESO

## 61 CYGNI

# THE STAR THAT CHANGED EVERYTHING

In the newly released *History of the Universe in 21 Stars (and 3 Imposters)*, the star 61 Cygni has been revealed to be the smoking gun in our understanding of the cosmos

Written by Giles Sparrow




Step outside and take a look at the early evening sky in summer and autumn and the constellation of Cygnus, the Swan, is hard to miss. This prominent cross-shaped constellation hangs high overhead, looking like a swan with outstretched wings and a long neck stretching along the Milky Way towards the southern horizon. The bright-blue star Deneb marks the Swan's tail high in the sky - the upper-left corner of the famous northern 'Summer Triangle' - while binoculars show that Albireo, on the tip of its beak, is a beautiful double star.

Cygnus is packed with beautiful and fascinating objects, so it's easy to overlook 61 Cygni, an apparently insignificant star tucked behind the Swan's right or eastern wing. But it's worth a look, not only because binoculars will show it as an attractive double star - a pair of yellow-orange stars separated by roughly the same diameter of Saturn in Earth's skies - but also because of its pivotal role in the history of astronomy. Out of all the stars in the sky, 61 Cygni was the first one to have its distance precisely measured, proving conclusively that the stars are blazing objects like our own Sun seen over vast distances.

Ancient and medieval astronomers mostly believed in an Earth-centred model of the universe - a system with Earth sitting at the centre of the cosmos, orbited by the Moon, Sun and planets, with the stars as either tiny lights affixed to an outer, all-encompassing sphere, or holes in that sphere permitting light to shine through from beyond. In general the universe was assumed to be compact, with the stars not much further beyond Saturn, then the most distant and slowest moving planet.

This view was shattered in the early 17th century. Early telescope observations by Galileo and others revealed moons orbiting Jupiter - conclusive proof that not everything in the universe circled the Sun - while Johannes Kepler made the theoretical breakthrough that orbits were usually ellipses rather than perfect circles. Together these discoveries backed up the idea of a Sun-centred or heliocentric universe, which had been on the table since Polish priest Nicolaus Copernicus published his controversial book *On the Revolutions of the Heavenly Spheres* from his deathbed in 1543.

One of several quite reasonable objections to the idea of Earth moving around the Sun was why our changing point of view didn't affect the positions of the stars through the year. Surely if our point of view looking towards distant stars was changing by tens of millions of miles over the course of a year, the stars should appear to move back and forth due to the same effect that makes objects near at hand shift their apparent direction when seen from two slightly different viewpoints, called parallax. Most astronomers reconciled the evidence by concluding that the stars must lie at truly vast distances from Earth - so far away that parallax was undetectable to the simple telescopes of the time.

Nevertheless, the quest to measure parallax became a major preoccupation for astronomers over almost two centuries. It was seen as a door through which the scale of the universe itself could be revealed - but how did the search for a star with a detectable shift zero in on the obscure 61 Cygni?

The star first drew attention to itself when its double nature was spotted by Astronomer Royal James Bradley from the Royal Observatory at

**Below:** The near-twin stars of 61 Cygni race across the sky, revealing their proximity to Earth

Source: Wikipedia Commons © IndividusObservantis

"CYGNUS IS PACKED WITH BEAUTIFUL AND FASCINATING OBJECTS, SO IT'S EASY TO OVERLOOK 61 CYGNI, AN APPARENTLY INSIGNIFICANT STAR"


# 61 CYGNI: THE FLYING STAR

61 Cygni is an unremarkable star system – if not for its proximity to Earth

### Flying through the heavens

The twin stars of 61 Cygni first drew attention to themselves because of their high proper motion against more distant background stars – they move across the sky at a rate equivalent to the width of a full Moon every 464 years.

### Heavenly pair

The two stars orbit each other in around 680 years, and are currently separated by 18 seconds of arc – about the width of Saturn as seen from Earth – and so can be distinguished from each other using binoculars or a small telescope.

### Twin suns

Both stars in the system are orange dwarfs – stars less massive than the Sun at about 0.7 and 0.6 solar masses and shining with 15 and 8 per cent of its light output.

### Telltale wobble

Around 11.4 light years from our Solar System, the two stars are close enough to shift slightly back and forth when viewed from different points on Earth's orbit. This shift amounts to a parallax angle of 0.285 arc seconds on either side of their central point.

**Above: The ESA's Gaia spacecraft has provided accurate measurements from above Earth**

Greenwich in September 1753. Over the following decades the stars were occasionally visited by astronomers keen to investigate the nature of such close pairs, but it was not until 1792 that Italy's Giuseppe Piazzi, a Catholic priest whose recently founded Palermo Observatory incorporated state-of-the-art equipment for measuring stellar positions, noticed something strange: the two stars had shifted position, and now lay slightly but unmistakably northeast of the location first reported by Bradley.

At the time Piazzi made a note of this unusual drift through the sky, a phenomenon that astronomers call 'proper motion', but he did not confirm it until 1804, when he revisited the star while compiling a detailed stellar catalogue. In the intervening years Piazzi had found fame through his discovery of Ceres, the largest asteroid and the first object to be discovered orbiting between Mars and Jupiter. Careful checking now confirmed his suspicion that 61 Cygni was moving across the sky at a surprisingly rapid rate of 4.1 seconds of arc per year, equivalent to the width of an average full Moon every 464 years. After the catalogue was published in 1806, 61 Cygni soon garnered the nickname of 'Piazzi's Flying Star'.

> "Out of all the stars, 61 Cygni was the first one to have its distance precisely measured"

Proper motion of the stars in Earth's skies is caused by a combination of their real drift through space and Earth's own drift as it is carried along with the Sun and the rest of the Solar System. Unlike the repeating back-and-forth drift expected from parallax, it manifests itself as a steady crawl in one particular direction across the sky, slowly rearranging the shapes of constellations over many thousands of years. With parallax itself still elusive, however, astronomers had realised that you could use proper motion as a neat proxy for a star's likely distance from Earth. Based on the reasonable assumption that stars travel at similar average speeds through space, then the closer the star is, the faster it will appear to move across the sky. 61 Cygni turned out to have the largest proper motion yet discovered, and was therefore immediately recognised as one of the closest stars to Earth. This made it a perfect target for ongoing attempts to measure our shifting cosmic point of view.

Even by the early 19th century, however, the challenge of detecting a star's parallax remained a daunting one, involving precise measurement of distances less than one second of arc or 1/3,600th of a degree. To accurately measure these tiny shifts, early parallax hunters had to battle not only the relatively primitive quality and low power of their telescopes, but also the effects of the atmosphere blurring the sharpness of star images – and even

the simple difficulty of knowing where, in terms of precise direction in the sky, their telescopes were actually pointing.

Early attempts at finding a solution therefore employed some ingenious lateral thinking. Bradley, for instance, long before his encounter with 61 Cygni, figured out a way to test the parallax of a moderately bright star called Eltanin, or Gamma Draconis. His approach measured the angle between Eltanin and the zenith - the point directly overhead - with pinpoint accuracy at the exact moment the star crossed the north-south line across the sky, so that he could be certain of Eltanin's precise position.

Bradley chose Eltanin because it passes almost directly overhead from London, helping to minimise another troublesome effect we haven't even mentioned yet - atmospheric refraction. As if the parallax quest didn't throw up enough challenges, astronomers also have to deal with the fact that as well as rippling and blurring the light from stars, Earth's atmosphere also deflects light rays onto new paths. The effect is strongly linked to the altitude at which a star appears in the sky, and so Bradley and his collaborator Samuel Molyneux decided to avoid the issue as much as possible by looking at an object almost directly overhead.

When Bradley and Molyneux began measuring Eltanin's position in December 1725, they soon found that the star was moving. But from the outset the results were puzzling: Eltanin was moving southwards at a time when parallax should have already put it at its southernmost point in the sky. By March its motion finally slowed and reversed, and it then tracked northwards until September when it reversed again. Two more years of observation confirmed the turning points were consistently three months out, with Eltanin always switching direction in March and September rather than June and December as predicted.

Bradley soon realised that they had discovered an entirely unconnected piece of evidence for Earth's motion - an effect known as aberration of starlight. This is a change in the angle at which starlight approaches Earth due to our motion around the Sun - if you think about raindrops falling at a steady angle while you stand still, and then imagine how their angle changes when you're walking in different directions, you'll get the picture. Because Earth's axis in space points in a constant direction as we make our annual trip around the Sun, the angle at which starlight falls towards Earth changes slightly in spring and autumn.

The complexities of aberration added further burdens to the already-difficult task of measuring parallax, but astronomers are a persistent breed, and thus the search continued throughout the 18th century and into the 19th, occasionally enlivened by triumphant announcements, nitpicking rebuttals and embarrassed retractions. It was not until the 1830s, however, that improved technology and skilful observing finally delivered an irrefutable parallax measurement.

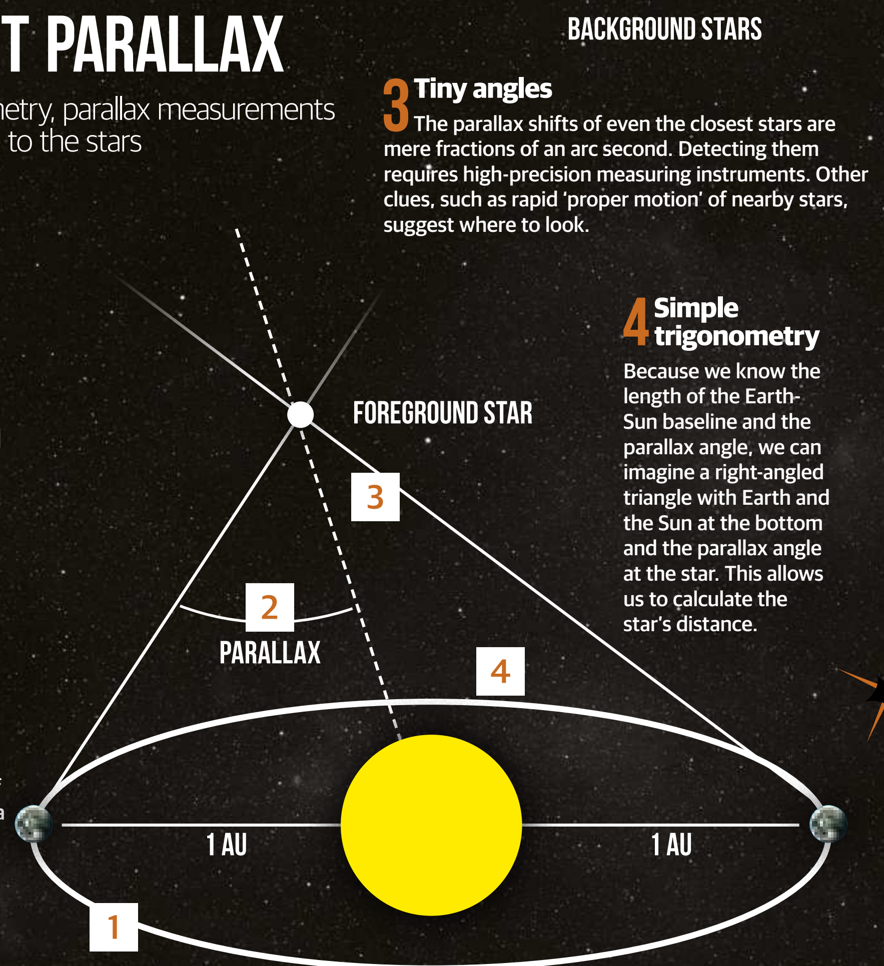
In the end the race came down to two of the 19th century's finest observers: Friedrich von Struve and Friedrich Wilhelm Bessel. Both benefited from the fact that by this time clockwork-driven telescope mounts could be used to keep pace with the sky's apparent rotation and stop their target stars rapidly drifting out of view under high magnifications. And both also followed a suggestion first made by William Herschel in the 1780s - that the best

## EXTENSIONS OF PARALLAX

**The 'annual parallax' method used by Bessel to measure nearby stars paved the way for other ingenious methods of distance measurement. Statistical parallax uses the proper motions of stars as a direct distance indicator on the assumption that, on average, more distant stars will move more slowly through the sky. Dynamical parallax calculates the size of the orbit in a binary star system and compares that to the stars' measured separation in the sky. Cluster parallax methods use various tricks to guess the size or average proper motion of distant star clusters and therefore estimate their distance.**

## ALL ABOUT PARALLAX

Using simple geometry, parallax measurements reveal the distance to the stars




**1 Earth's orbit** As Earth orbits the Sun during the course of a year, it moves around a circle with a diameter of 300 million kilometres (186 million miles). This creates a slight shift in our view of the surrounding universe.

**2 Parallax shifts** Nearby stars appear to shift their positions in the sky by a larger angle than more distant stars. Parallax shifts can be measured relative to more distant unshifting stars or on the fixed grid of celestial coordinates.

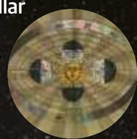
**3 Tiny angles** The parallax shifts of even the closest stars are mere fractions of an arc second. Detecting them requires high-precision measuring instruments. Other clues, such as rapid 'proper motion' of nearby stars, suggest where to look.

**4 Simple trigonometry** Because we know the length of the Earth-Sun baseline and the parallax angle, we can imagine a right-angled triangle with Earth and the Sun at the bottom and the parallax angle at the star. This allows us to calculate the star's distance.

# TIMELINE OF THE DISCOVERY OF 61 CYGNI

## 1543 THE COPERNICAN REVOLUTION

Copernicus published his influential argument that the Sun is at the centre of the Solar System. As evidence to support this idea mounted, astronomers hoped to clinch the argument by discovering stellar parallax. When they didn't, they concluded that the stars must be very far away.



## 1718 PROPER MOTION

Halley reported evidence that the positions of certain bright stars had shifted significantly since they were catalogued by ancient Greek astronomers. This was the first sign of proper motion – the slow rearrangement of the stars in Earth's skies due to their motion through space.

## 1727 ABERRATION OF STARLIGHT

While attempting to measure the parallax of the star Eltanin in Draco, Bradley discovered a shift in the apparent positions of all stars throughout the year caused by aberration of starlight – changes in the angle at which light approaches Earth caused by our motion through space.

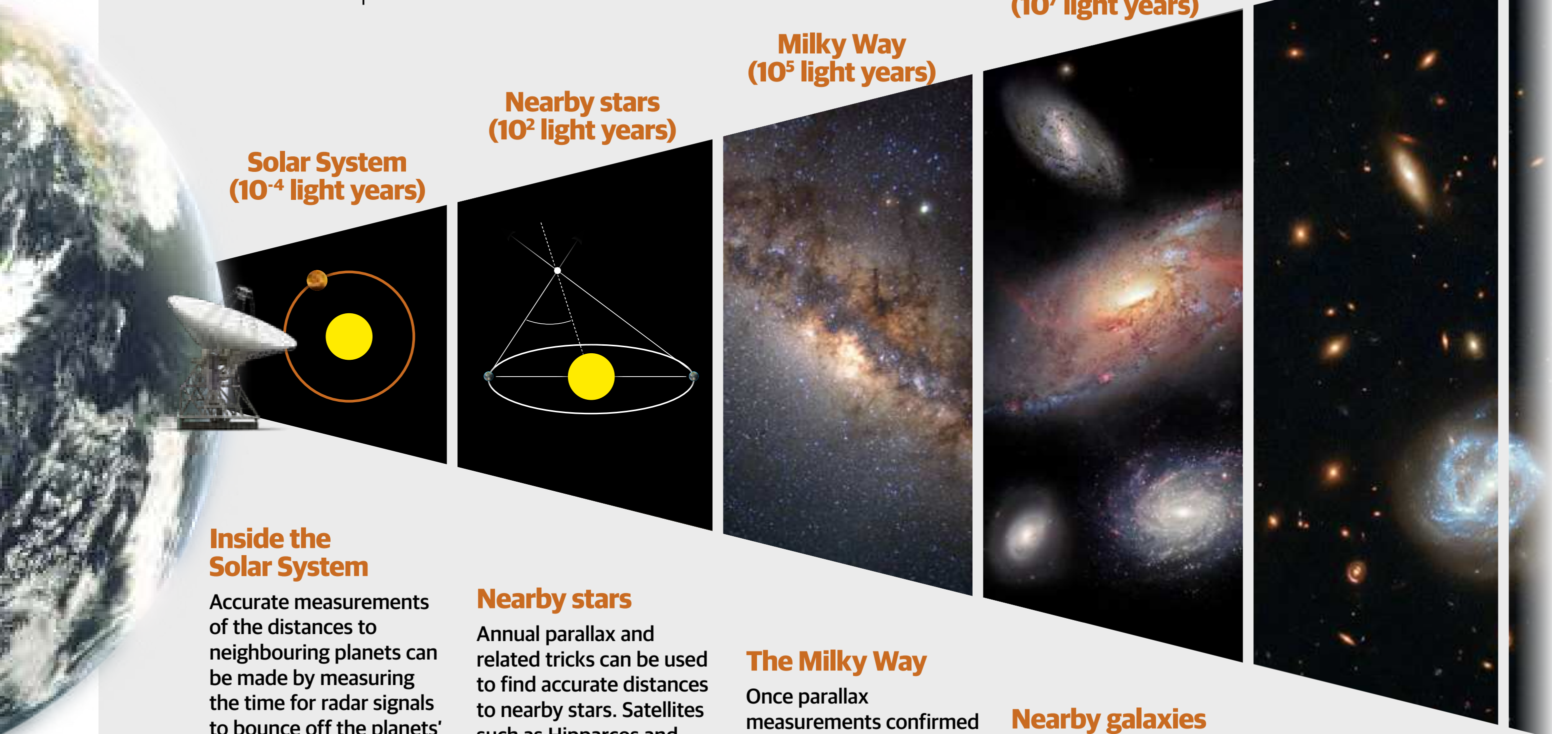
## 1804 A FLYING STAR

Giuseppe Piazzi confirmed his earlier suspicion that 61 Cygni, the double star in Cygnus first reported by Bradley half a century earlier – has a very high proper motion of 4.1 seconds of arc per year, suggesting it is nearby and a potential target for parallax measurements.



# THE COSMIC DISTANCE LADDER

How do we work out distances as they increase across the vastness of space?




### Inside the Solar System

Accurate measurements of the distances to neighbouring planets can be made by measuring the time for radar signals to bounce off the planets' surfaces and return. Combined with models of planetary orbits, these provide an accurate scale for the Solar System.

### Nearby stars

Annual parallax and related tricks can be used to find accurate distances to nearby stars. Satellites such as Hipparcos and Gaia have extended annual parallax measurements to much greater distances.

### The Milky Way

Once parallax measurements confirmed the true luminosity of some stars, clear relationships began to emerge between luminosity and spectral features such as a star's colour. Using a star's spectrum to estimate its inherent luminosity, astronomers can then make an educated guess at its likely distance.

### Nearby galaxies

Several types of variable star display a relationship between the period of their pulsations and their true average luminosity. The most useful of these are brilliant yellowish stars called Cepheid variables. Measuring the periods of Cepheids in nearby galaxies reveals their distance.

### The distant universe

Type Ia supernovae are a form of exploding star that always peak at the same luminosity. Though infrequent, they can give a rare clue to the distance of the most remote galaxies. Astronomers also use a statistical trick called the Tully-Fisher relation, which estimates the typical luminosity of certain galaxies within clusters.

> "THE STARS WERE TRANSFORMED INTO DISTANT BUT MEASURABLE OBJECTS"

## 1837 RACING FOR PARALLAX

Friedrich von Struve published an accurate preliminary estimate of parallax for the bright star Vega, or Alpha Lyrae, but continuing observations eventually led him to a larger and less accurate final figure by 1840. His original figure was very close to modern-day calculations.

## 1838 BESSEL'S TRIUMPH

Friedrich Bessel completed his parallax measurements of 61 Cygni, demonstrating its annual parallax of 0.314 seconds of arc and indicating a distance of around 10.3 light years – ten per cent below current estimates. He also worked out the orbital period of the binary pair.

## 1913 THE HERTZSPRUNG-RUSSELL DIAGRAM

Building on earlier work by Danish chemist and astronomer Ejnar Hertzsprung, American astronomer Henry Norris Russell used the parallax of nearby stars to plot a diagram comparing their true luminosity with their colour or 'spectral type'. The diagram reveals patterns in the properties of stars that prove to be the key to understanding stellar evolution.

## 2013 MEASURING THE MILKY WAY

The European Space Agency launched Gaia, an advanced satellite designed to carry out a decade-long parallax survey in unprecedented detail. Gaia's measurements offer accurate estimates of stellar distances as far off as the centre of the Milky Way, sitting some 26,000 light years away.

© Adrian Mann

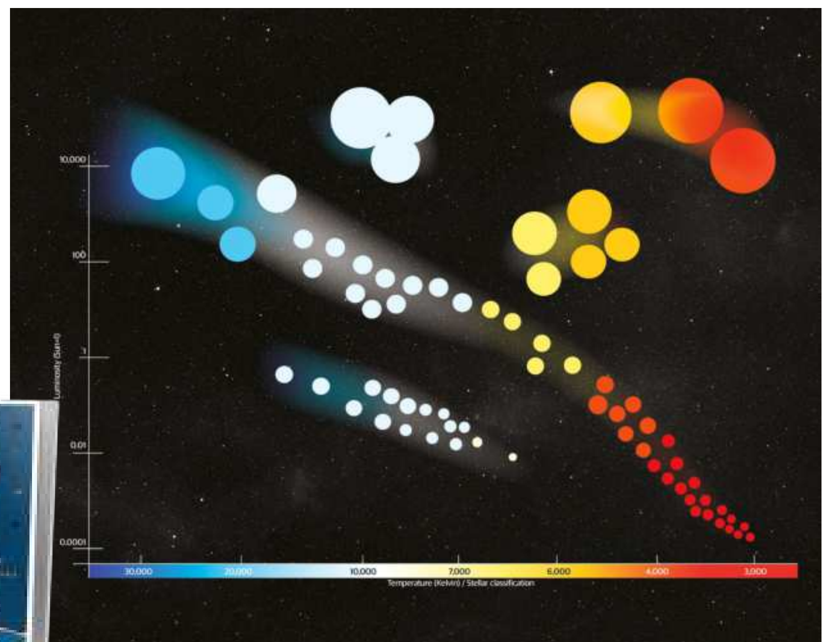
approach was to look for changes in a target star's position relative to others that lay nearby in the sky rather than trying to track its precise location on the celestial sphere.

Struve's effort focused on Vega, among the brightest and best known of all stars, while Bessel concentrated on the far more obscure 61 Cygni. As it turns out, Vega is about twice as far away as 61 Cygni, and has slightly less than half the parallax, making Struve's task considerably more difficult. Struve was also using a traditional 'micrometer' eyepiece – a design in which two fine parallel wires are projected into the observer's field of view. The separation between these wires can be changed very gradually by turning an adjustment screw, and you can then translate the distance between the wires into an angular separation in the sky with some fairly simple maths. Struve began to track Vega's relative motion in late 1835, and by 1837 he had 17 measurements that allowed him to publish a preliminary figure for Vega's parallax of one-eighth of a second of arc – close to the modern value. Had he stopped there he might perhaps have claimed the prize, but instead he continued, and by 1840, when he published his final result, his estimate had doubled, putting it far adrift of later measurements.

Bessel, in contrast, used a different sort of set-up known as a heliometer. This was a refracting lens-based telescope whose main or objective lens was carefully cut into two halves. The separation produced a double image in the eyepiece, and one half-lens could be finely adjusted with a screw system so that when the images of two separate stars overlapped, the heliometer revealed the angular separation between them. Beginning in August 1837, Bessel managed to take 98 parallax measurements of 61 Cygni over just 13 months. He quickly processed his data and published his results by way of a letter to Sir John Herschel, now president of the Royal Astronomical Society in London, on 23 October 1838.

**Right:** The Hertzsprung-Russell diagram plots magnitude against spectral types

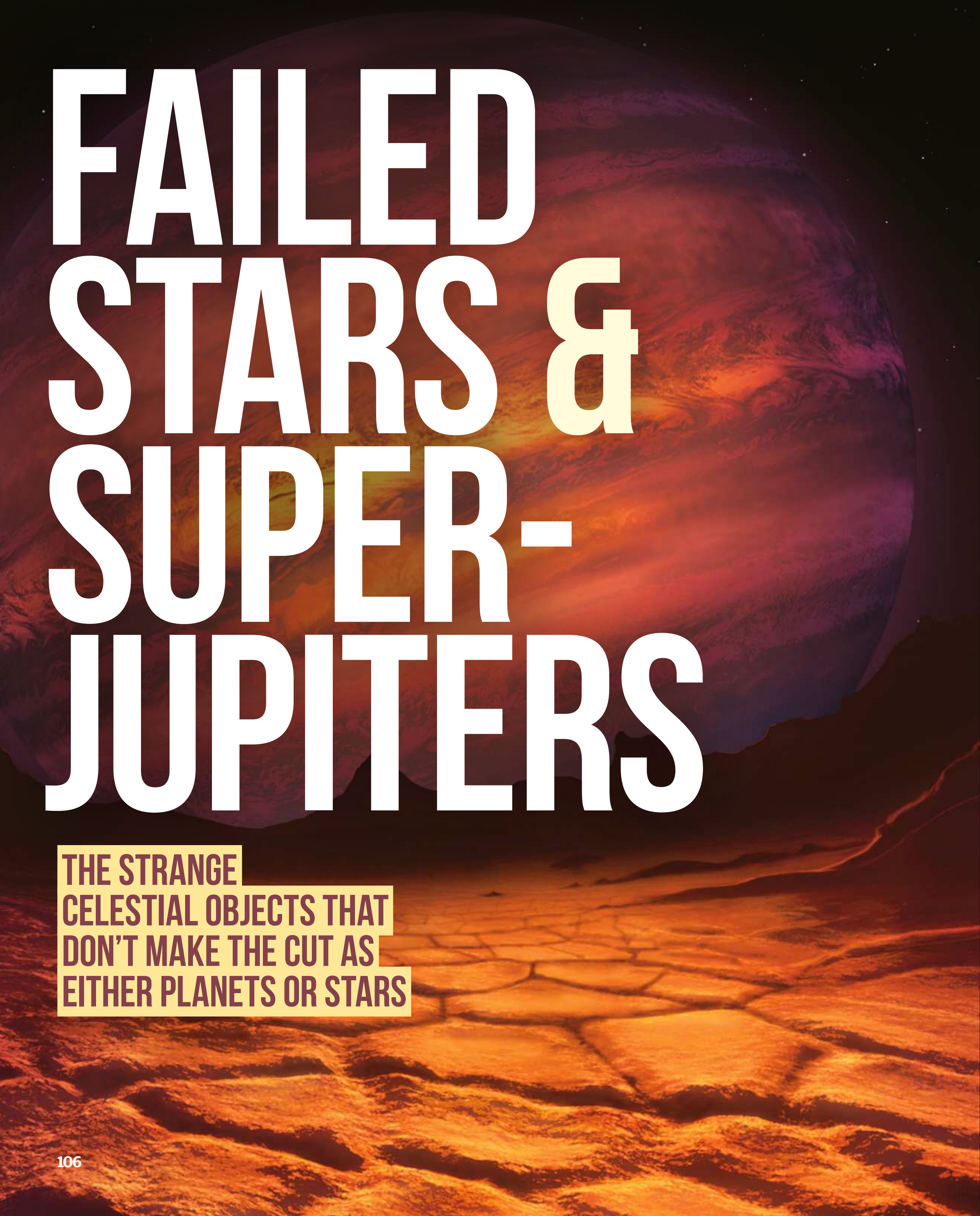
**Below:** Discover more about the stars in Giles Sparrow's new book




Bessel's calculations were a tour de force, and far more convincing than Struve's more limited data. He not only estimated the parallax of the overall 61 Cygni system as 0.314 seconds of arc – equivalent to a distance of 10.3 light years – but also analysed the relative motions of the two stars and showed that they took at least 540 years to orbit each other. These figures stand up remarkably well even today, where the system's parallax has been refined to 0.286 arcseconds, its distance to 11.4 light years and its orbital period to around 678 years.

Herschel referred to Bessel's measurements as the moment when the "sounding line in the universe of stars had at last touched bottom" – they marked the beginning of a new era in which stars were transformed from points of light in the sky into distant but measurable objects whose physical properties can be analysed and understood. Even today when it is measured to amazing precision by orbiting satellites such as the European Space Agency's (ESA) Gaia, parallax remains our only method of directly measuring the distance to objects in the wider cosmos, and provides a happily stable first rung on a ladder of cosmic distances that gets increasingly rickety as it extends further from the certainties of Earth. We should all spare a thought for the obscure double star in Cygnus where it all began.

**Giles Sparrow**
*Space science writer*
The author of over 20 books on popular science, Giles holds a degree in astronomy and is an editor specialising in science and technology.



# FAILED STARS & SUPER-JUPITERS

**THE STRANGE CELESTIAL OBJECTS THAT DON'T MAKE THE CUT AS EITHER PLANETS OR STARS**

The brown dwarf is seen as a stellar failure, a dropout from the school of star formation. These gigantic objects, with their puffy, gaseous outer layers, are the universe's students that didn't quite make the grade. In brown dwarfs, nuclear fusion – the process that gives stars their power – has given up the ghost, leaving them relatively cold, with some no hotter than the human body. Neither planet nor star, brown dwarfs fall into the grey area between the most massive gas giant planets like Jupiter – hence why they're known as 'super-Jupiters', because of their massive, gaseous nature – and the smallest stars. Their existence blurs the lines between what is a planet and what is a star, forcing us to question the differences between how planets and stars form.

Stars form when clouds of molecular gas collapse under gravity and condense until the pressure and temperature at the centre of the cloud is so great that nuclear fusion reactions – which turn nuclei of the element hydrogen into heavier helium nuclei – ignite. This kind of top-down formation is one of the key differences between how stars and planets form. Meanwhile, the worlds of our Solar System and many others that astronomers have been studying over the past 25 years form through a bottom-up process, where a core gradually builds up, becoming bigger and bigger. For the most massive planets, the core has enough gravity to begin stealing gas from the proto-stellar nebula around it, and this is where gas giants such as Jupiter and Saturn got their hefty atmospheres.

Brown dwarfs form like stars, collapsing directly out of a gas cloud like a star in a top-down process. Clearly they are intended to become stars, but something happens along the way that causes them to become runts of the stellar litter, smaller and cooler than even chilled-out red dwarf stars.

The universe actually seems to favour smaller objects. The so-called mass function describes the distribution of masses of the objects that are created in a star-forming nebula. A handful will be massive stars that will one day die as supernovae. More will be Sun-like stars. Even more will be red dwarfs, smaller and cooler than our Sun. And the most common type of object that will form in a nebula will be brown dwarfs. This is backed up by observations with the Hubble Space Telescope of the Orion Nebula, which discovered 50 brown dwarfs amid the newborn stars of the Trapezium Cluster. There will undoubtedly be more brown dwarfs in the Orion Nebula, but they are difficult to spot because they are so cool and dim. Hubble used its near-infrared camera to find the brown dwarfs – at their low temperature, brown dwarfs give out most of their light in thermal infrared.

In fact, so difficult are they to spot that the first brown dwarf wasn't discovered until the late-1980s, when astronomers Ben Zuckerman and Eric Becklin of the University of California, Los Angeles, found a suspected brown dwarf called GD 165B – although there remains some lingering doubt that it could just be a very low-mass star.

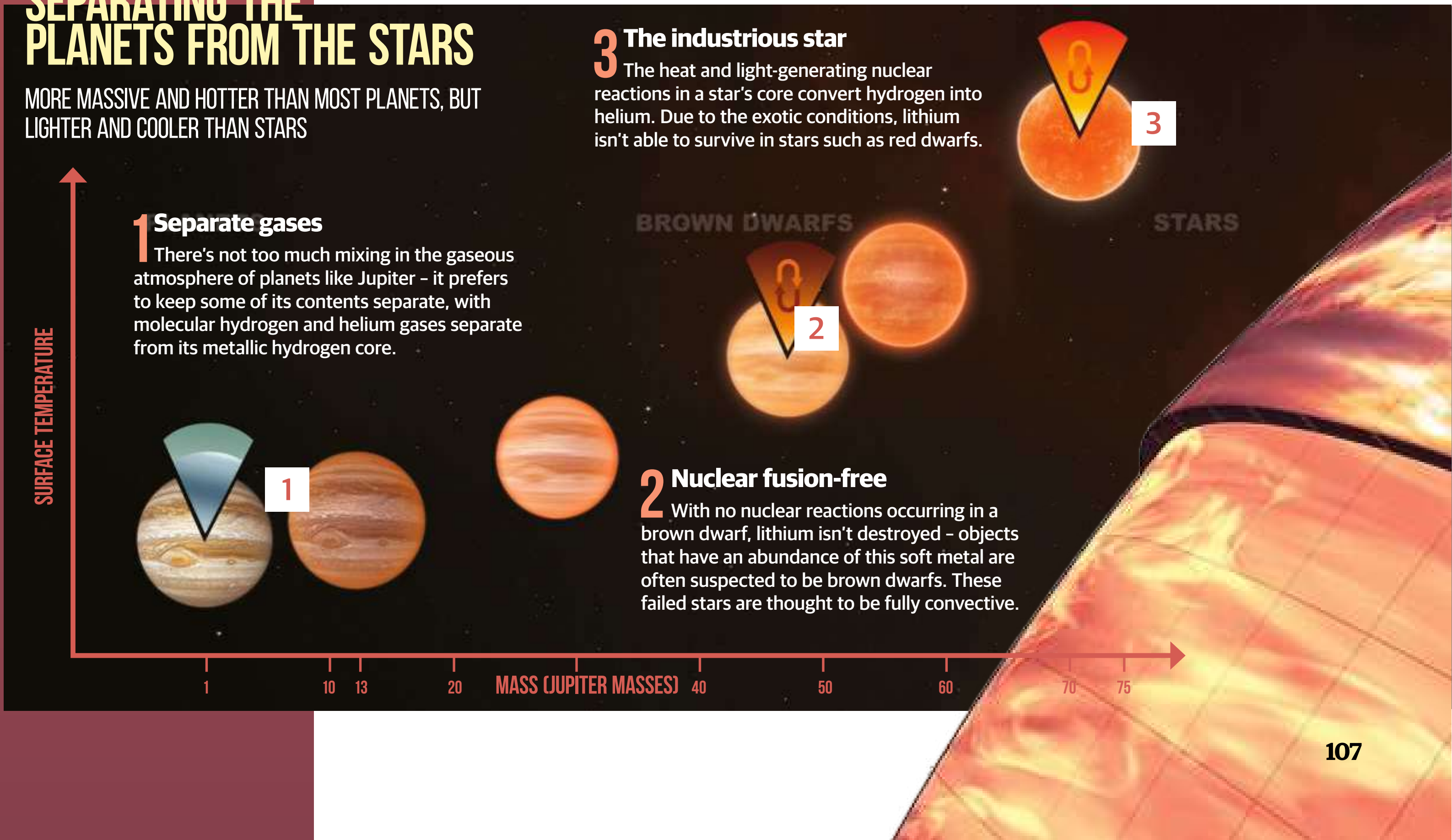
Astronomers then had to wait nearly another ten years before finding more brown dwarfs, with Teide 1 in the Pleiades star cluster being discovered in 1995. Brown dwarfs had been theorised to exist long before the 1980s, and it was actually Jill Tarter of SETI fame who came up with the name 'brown dwarf' in 1975. Previously they had been known as black dwarfs, but this caused confusion with the other black dwarfs, which are what white dwarfs will eventually become when they cool down over trillions of years. Besides that, in actual fact brown dwarfs are not black, or even really brown – they are more of a magenta shade.

Huge advances in our understanding of brown dwarfs have been made in recent years, mainly thanks to NASA's Wide-field Infrared Survey Explorer (WISE) satellite. WISE spent a whole year scanning the sky in mid-infrared light, wavelengths in which cool brown dwarfs should just pop into view. "The brown dwarfs jump out at you like big, fat, green emeralds," says WISE deputy project scientist Amy Mainzer. They appear green in WISE's images because their temperatures are coded to false colours.

WISE proved to be a prolific brown dwarf discoverer, and it ended up finding the coolest brown dwarfs discovered so far. They are so cool, in fact, that astronomers had to come up with a whole new classification for them.

## SEPARATING THE PLANETS FROM THE STARS

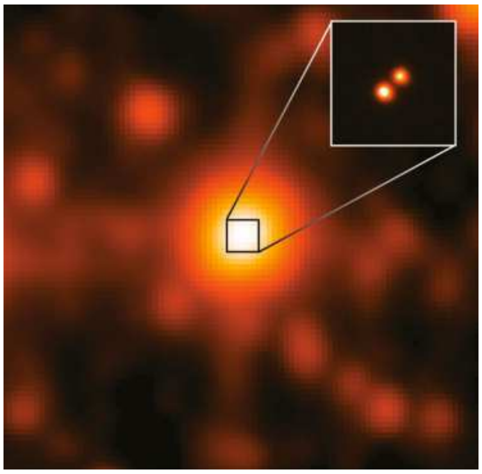
MORE MASSIVE AND HOTTER THAN MOST PLANETS, BUT LIGHTER AND COOLER THAN STARS



Stars are grouped into types dependent on their temperature and luminosity. The hottest, most luminous stars are termed O-types. Next are B-types, then A-types, then F-types, G-types – like the Sun – K-types and M-types, the latter of which are red dwarfs. But brown dwarfs are even cooler than red dwarfs, so new types were needed to describe them, namely L and T-types. In 2014, however, astronomers using WISE found a brown dwarf, called W0855-0714, which was so cold that it had a temperature of between -48 and -13 degrees Celsius (-54.4 and 8.6 degrees Fahrenheit). This brown dwarf was described as a Y-type, and only a few dozen more have subsequently been identified. Scientists have not even been able to rule out the possibility of one or more brown dwarfs lying closer to the Sun than the current nearest star, Proxima Centauri, which is 4.2 light years away.

Brown dwarfs are described as being between 13 and 80 times the mass of Jupiter, but W0855-0714 comes in below that, weighing only as much as between three and ten Jupiters, showing how difficult it is to define what a brown dwarf is, at least based on its mass. It has been speculated that it could be an escaped planet, but astronomers suspect it is more likely to be a brown dwarf, simply because there should be so many brown dwarfs that the odds are against it being a rogue planet.

Brown dwarfs may form like stars, but they look more like planets, to the extent that they even have weather and clouds. For example, one brown dwarf, called ULAS J222711, appeared redder than other normal brown dwarfs. Under further inspection, astronomers from the University of Hertfordshire found that it was clouds scattering sunlight that were giving ULAS J222711 its red hue – but these were certainly not clouds like the fluffy water-vapour versions we have in Earth's sky.



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"The thick clouds on this particular brown dwarf are mostly made of mineral dust, like enstatite and corundum," says the University of Hertfordshire's Federico Marocco. "Not only have we been able to infer their presence, but we have also estimated the size of the dust grains in the clouds." These dust grains were calculated to be about 0.5 micrometres (0.5 millionths of a metre or 20 millionths of an inch) across. On the brown dwarf W0855-0714 there is also evidence of frozen clouds of sulphides and water-ice, while gases such as methane, hydrogen sulphide and ammonia are taken as a given. "If you could bottle up a gallon of a brown dwarf's atmosphere and bring it back to Earth, smelling it wouldn't kill you, but it would stink pretty bad, like rotten eggs with a hint of ammonia," Mainzer explains.

Most brown dwarfs could also be stormy, further cementing their similarities with Jupiter-like worlds. WISE's infrared predecessor, the Spitzer Space Telescope, has found signs of patchiness in the cloud cover of brown dwarfs, which could equate to roiling storm regions that sport terribly strong winds, enormous lightning strikes and rainfalls – not of water, but of molten sand and iron. "What we see here is evidence for massive, organised cloud systems, perhaps akin to giant versions of the Great Red Spot on Jupiter," said Professor Adam Showman of the University of Arizona.

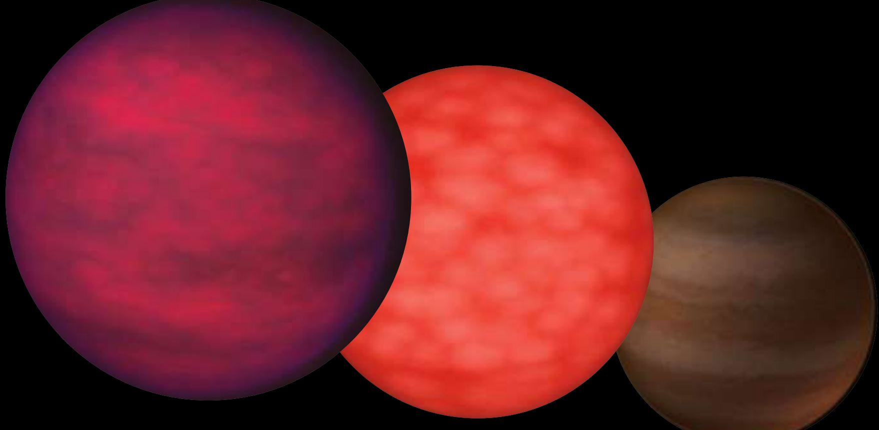
By teaming up Spitzer with Hubble, astronomers were able to look at brown dwarfs in different wavelengths of infrared light, which are able to peer down into different layers of a brown dwarf's atmosphere. As the brown dwarf rotates, variations in the amount of cloud cover and the size of the storms affects the brightness that the Hubble and Spitzer space telescopes can see. "These out-of-sync light variations provide a fingerprint of how a brown dwarf's weather systems stack up vertically. The data suggests that regions on a brown dwarf where the weather is cloudy and rich in silicate vapour deep in the atmosphere coincide with balmier, drier conditions at higher altitudes, and vice versa," explained Showman.

But where do brown dwarfs get the energy from to drive weather and planet-sized storms? On Earth the energy for our weather systems comes from heat emitted by the Sun. Some brown dwarfs are found orbiting stars, but that doesn't explain where brown dwarfs without stellar companions get their heat from. A world like Jupiter, which is far from the Sun, still retains some residual heat within its core from the days when it was formed, and some of the heat of brown dwarfs will come from the same source. However, brown dwarfs have an advantage over worlds like Jupiter.

Although they are lacking too much mass to ever have the required pressures and temperatures in their cores to instigate nuclear fusion of hydrogen into helium, they can for a short while ignite nuclear fusion reactions of deuterium. The most massive brown dwarfs are also able to fuse lithium. Lithium does not exist in any significant quantities in normal stars either, so a search for lithium is a good test of whether an object is a brown dwarf or not. The smallest brown dwarfs, which are less

## TYPES OF BROWN DWARF

The different classes and colours of these cool stars



**T dwarf**
**Temperature:** 427 to 1,026°C (801 to 1,879°F)
**Colour:** Dark magenta
**Number found:** Over 600
**Contain:** Water, methane and ammonia gases

**L dwarf**
**Temperature:** 1,027 to 1,727°C (1,880 to 3,141°F)
**Colour:** Orange-red
**Number found:** Over 1,700
**Contain:** Clouds of 'hot dirt' and other condensates

**Y dwarf**
**Temperature:** Less than 327°C (620°F)
**Colour:** Brown
**Number found:** Approximately 30
**Contain:** Possibly water

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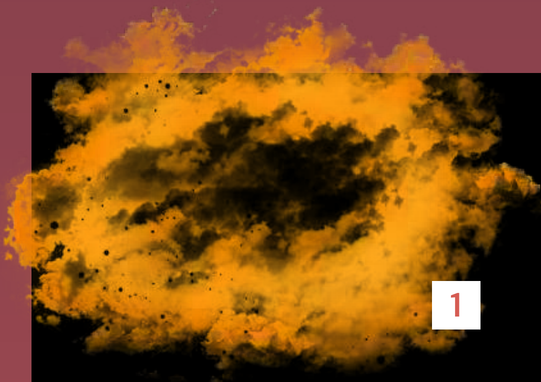
**Above:** At a distance of 6.5 light years away, Luhman 16 is the closest brown dwarf binary to Earth

**Right:** An infrared image of the Pleiades, or 'Seven Sisters', by the Spitzer Space Telescope




# THE MAKING OF AN EPIC FAIL

What happens when collapsing clouds of gas and dust don't make it as stars

## 1 The stellar nursery

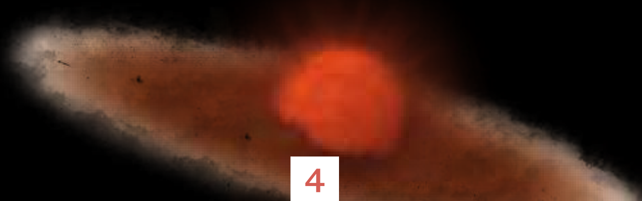
Just like main sequence stars like our Sun, these objects come from the collapse of a cloud of gas and dust under its increasing gravity.


## 2 The young star

When a cloud of gas and dust caves in, gravity begins to pile up the material tightly to make a very young star – known as a protostar – at its centre.


## 3 Failure to fuse

In a main sequence star, gravity pushes so strongly inward that hydrogen fusion is kick-started in the core. The brown dwarf never reaches this stage, and before the temperatures get hot enough for hydrogen fusion to start, the brown dwarf reaches a stable state.

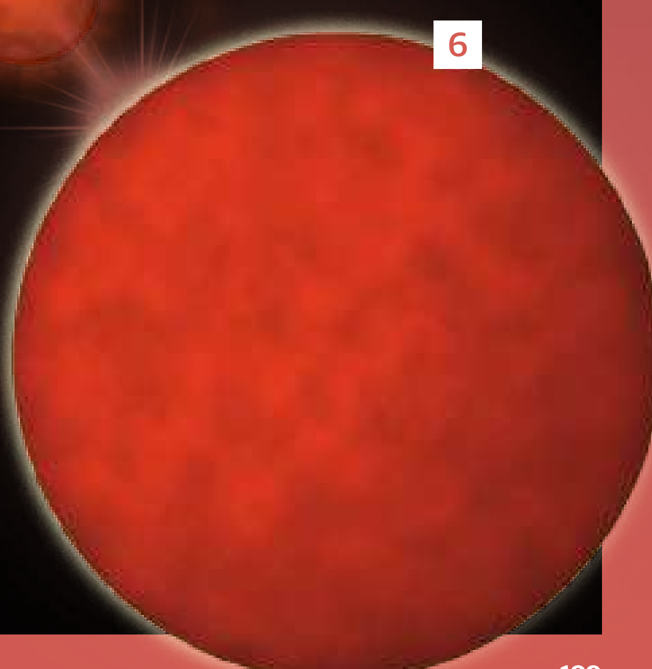



## 4 The cool brown dwarf

Since they are not very visible to the human eye, telescopes need to observe them in infrared wavelengths to pick up their heat, which is considered to be very low compared to their blazingly hot and bright stellar cousins.

## 5 Brown dwarf types

Just like stars, which are categorised by a spectral class, brown dwarfs sit in the classes L, T and Y. The coolest is the rare Y dwarf, which can be colder than the human body. Some – but not all – hotter M-class stars can also be brown dwarfs.




## 6 Colours and flavours

Belonging to different classes means that brown dwarfs contain different gases and appear in differing colours. A T dwarf appears as a dark magenta and contains a gaseous mixture of methane, water and ammonia, while Y dwarfs take on a browner shade and are likely to contain a good amount of water.


© NASA/ESA

Above: The first brown dwarf to be verified, known as Teide 1, rests in the famous Pleiades star cluster

## BROWN DWARF DISCOVERY

NASA's WISE telescope is an expert when it comes to hunting down brown dwarfs

### 2011

The spacecraft confirms the existence of a new class of brown dwarf, known as the Y dwarf. These brown dwarfs can have temperatures as cool as the human body.

### 2013

The discovery of the closest brown dwarfs to Earth is announced. They were discovered using WISE at a distance of 6.5 light years away, and are locked in a binary system called Luhman 16.

### 2014

WISE discovers the coldest known brown dwarf so far, which has an ultra-cool temperature between -48 and -13 degrees Celsius (-54.4 and 8.6 degrees Fahrenheit).

### 2020

With the help of citizen scientists, two of the most planet-like brown dwarfs are discovered in the Milky Way's oldest population of stars.


© NASA

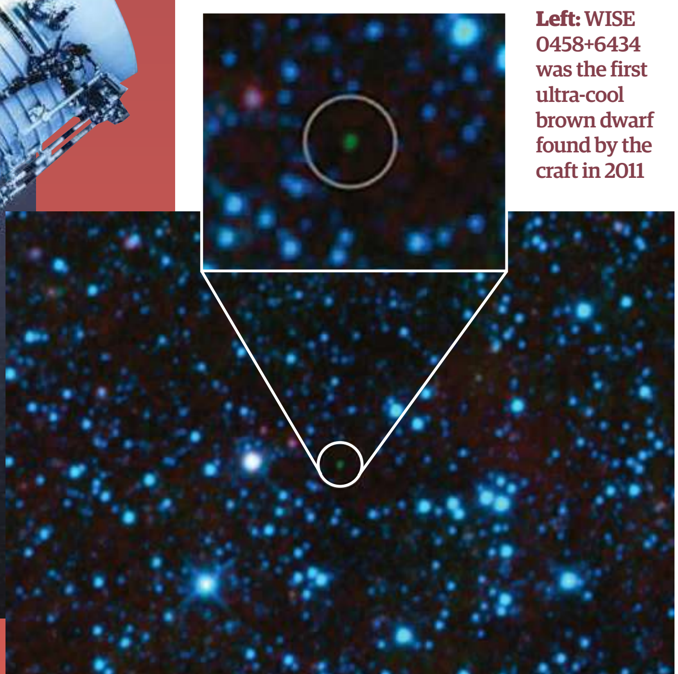
than 13 times the mass of Jupiter, are nowhere near hot enough in their cores for any fusion reactions. Nevertheless, those that are able to start the reactions can, for a short while, produce heat and energy this way, which resides in the star for billions of years after the fusion reactions have actually run themselves out.

Inside a star like the Sun, there are two zones. The innermost is the radiative layer around the nuclear core, where energy produced by fusion reactions is transported through radiation. It is this energy that holds the Sun up against the pull of its gravity. Above the radiative layer is the convective layer, where convection currents transport the energy the rest of the way to the Sun's surface. Brown dwarfs, however, are suspected to only have convective layers. This leads to their interiors being 'springy', so they can become more compressed with greater mass. This results in brown dwarfs that are not much larger than the diameter of Jupiter despite some having dozens of times more mass.

This could result in the surprising scenario where a planet orbiting a brown dwarf is actually bigger than the brown dwarf itself. Given brown dwarfs are not proper stars, it had been uncertain as to whether planets could form around them. However, the Atacama Large Millimeter/submillimeter Array (ALMA) in the Chilean desert has discovered a disc of dust and rubble around a brown dwarf, just like the planet-forming dust discs that astronomers find around young stars. The disc around the brown dwarf, which is known as ISO-Oph 102 and has 60 times the mass of Jupiter, contains millimetre-sized dust grains. In the planet-forming discs around young stars, these grains gradually begin to stick together, growing larger and larger until they build up into rocky planets.

"We were surprised to find millimetre-sized grains in this thin little disc," says Luca Ricci of California State University Northridge, who headed the team of astronomers that used ALMA to find this disc. "Solid grains of that size shouldn't be able to form in the cold outer regions of a disc around a brown dwarf, but it appears that they do. We can't be sure if a whole rocky planet could develop there, or already has, but we're seeing the first steps."

This leaves brown dwarfs facing something of an identity crisis. They form in the same way that stars do but are not stars, unable to fuse hydrogen into helium. They look like planets with weather systems, but are more massive and do not form like planets, yet they may be able to form planets orbiting around them. They are likely the most common type of object in the universe - some scientists even suspect there could be enough brown dwarfs to account for some of the missing mass that has been attributed to dark matter.
Yet despite all of this they will always be seen as failures, objects that couldn't become stars, when really we should see them as super-planets that take on some star-like qualities. The brown dwarf is truly a unique breed of object, capable of taking on the role of both planet and star, while possibly revealing more about our hidden universe.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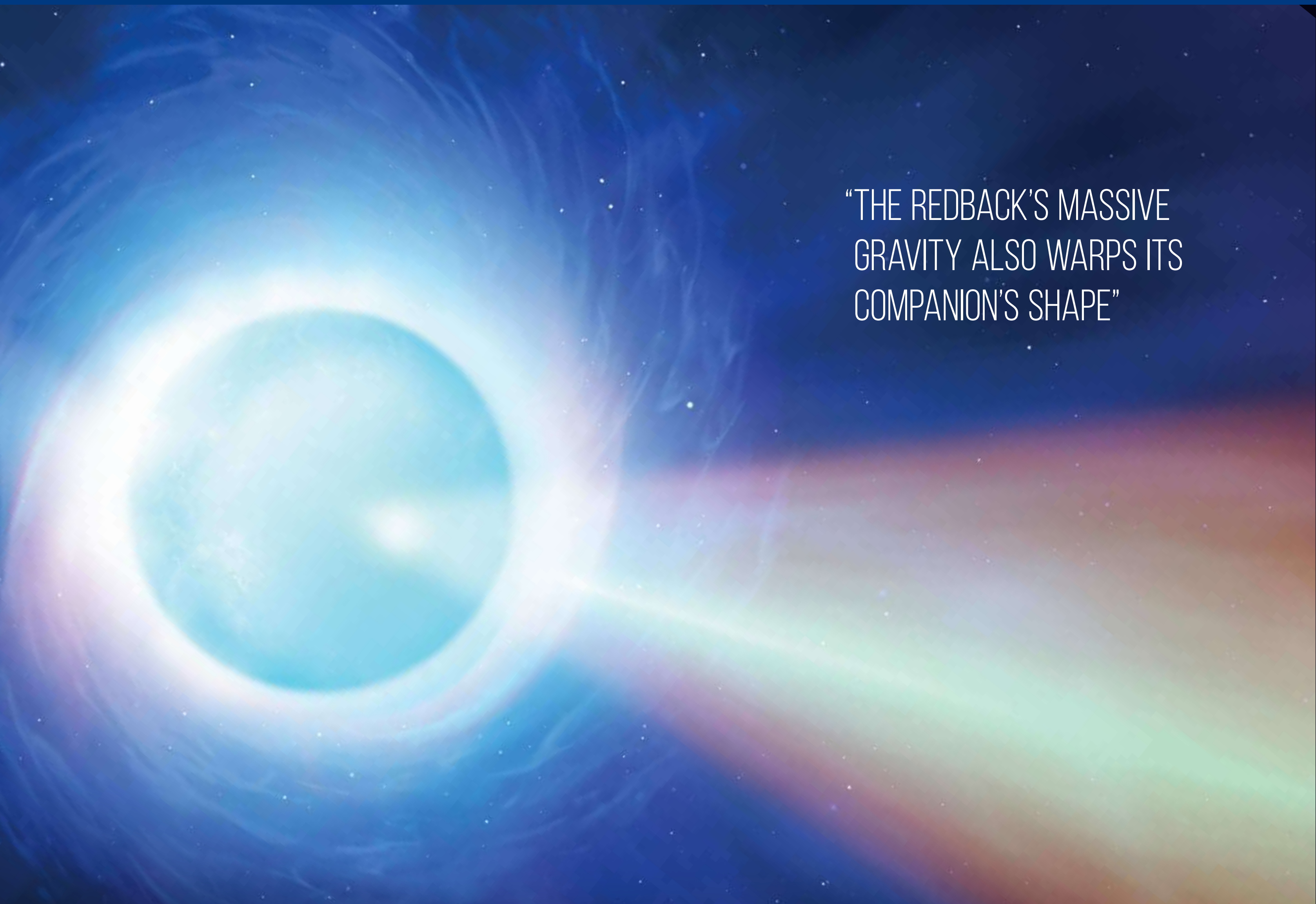
**Left:** WISE 0458+6434 was the first ultra-cool brown dwarf found by the craft in 2011



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"THE REDBACK'S MASSIVE GRAVITY ALSO WARPS ITS COMPANION'S SHAPE"

# STELLAR CANNIBAL'S MYSTERY SOLVED

## A fast-spinning neutron star is ripping its companion apart as they orbit one another

The mystery at the heart of an unexplained bright point of gamma-ray light in the sky has been solved: there's a deadly spider star flaying a second wimpier star to bits, sending out rapid-fire bursts of gamma radiation in the process.

'Black widows' and 'redbacks' in astronomy are species of neutron stars - the ultradense remnant cores of giant stars that exploded. Some neutron stars, called pulsars, rotate at regular intervals, flashing like lighthouses. The fastest spinning among them are millisecond pulsars. When a millisecond pulsar is locked in a rare tight orbit with a lightweight star, it slowly shreds its partner to bits with each rotation. These binary cannibals are known as black widow or redback stars, named after spider species. Now, with the help of citizen scientists, a team of researchers has revealed a new redback at the heart of a bright system known as PSR J2039-5617.

Since its discovery in 2014, researchers have suspected that PSR J2039-5617 contained a millisecond pulsar and a second star. The bright source of X-rays, gamma rays and visible light closely matched the expected traits of such a system. But proving it required lots of telescope data and more number crunching than a typical desktop computer could do in a century.

To prove that the star system was indeed a redback, the researchers leaned on the computing power of Einstein@Home, a project of the LIGO Scientific Collaboration and Germany's Max Planck Institute where more than 500,000 volunteers let their idle computers work together on complex astronomy problems.

In two months the researchers revealed that PSR J2039-5617 indeed houses a deadly redback, heating up one side of its companion star so that side appears brighter and bluer. The redback's massive gravity also warps its companion's shape, causing "the apparent size of the star to vary over the orbit," said Dr Colin Clark, a University of Manchester astronomer.

The redback star's radio emissions also sometimes get eclipsed by material blown off the surface of the companion star. All those features of the complex system produce strange, varying light patterns.

MYSTERIES OF THE UNIVERSE

# WHAT'S UP WITH THE MILKY WAY?

A fast radio burst was detected from within our galaxy for the first time. Are we closer to uncovering their origin?

Reported by David Crookes

On 28 April 2020, two ground-based radio telescopes detected an intense pulse of radio waves. It only lasted a mere millisecond but, for astonished astronomers, it was a major discovery, representing the first time a fast radio burst (FRB) had ever been detected so close to Earth.

Located just 30,000 light years from our planet, the event was firmly within the Milky Way, and it was, to all intents and purposes, almost impossible to miss. The Canadian Hydrogen Intensity Mapping Experiment (CHIME) and the Survey for Transient Astronomical Radio Emission 2 (STARE2) certainly had no problems picking it up. "CHIME wasn't even looking in the right direction and we still saw it loud and clear in our peripheral vision," says Kiyoshi Masui, assistant professor at the Massachusetts Institute of Technology. "STARE2 also saw it and it's only a set of a few radio antennae literally made out of cake pans."

Until that point, all FRBs had been observed outside of our galaxy. "They've been billions of light years away, making them a lot harder to study," says PhD candidate Pragya Chawla from McGill University in Canada. April's discovery was also notable for being the most energetic radio blast that astronomers have ever recorded in the Milky Way, but what made it most exciting is that scientists are now closer to determining the origin of FRBs than at any point since they were originally discovered.

## FRB 200428 BY NUMBERS

**3,000**
FRB 200428 was 3,000-times brighter than any other magnetar radio signal observed so far

**1**
Duration of the FRB in milliseconds

**30,000**
Number of light years away from Earth

**30**
Number of seconds it would take the Sun to emit as much energy

**1**
Number of bursts recorded from FRB 200428

**FIRST**
FRB detected with emissions other than radio waves

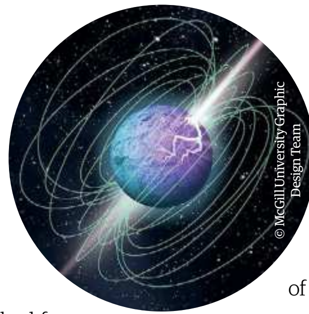
**30,000,000**
Estimated number of inactive magnetars in our galaxy

**30x**
less energetic than the weakest extragalactic FRB observed so far

**FIRST**
FRB firmly linked to a magnetar

**Right:** An artist's impression of the SGR 1935+2154 magnetar during an outburst, highlighting its complex magnetic field structure and beamed emissions

**Below:** An artist's impression of a fast radio burst with its different radio wavelengths – red being long and blue short – as they reach Earth




That happened in 2007, when Duncan Lorimer and David Narkevic were studying data taken by the Parkes radio dish in Australia. Discovering an FRB so close to home has been the breakthrough astronomers have wished for ever since. "We can learn more from a source that's 30,000 light years away than one that's a billion or more light years distance," Masui affirms. "We finally have a nearby source to study."

One of the major problems with detecting FRBs – aside from most of them having been so far away – is that they are so fleeting. They've been and gone in the blink of an eye despite being 100 million times more powerful than the Sun – they can release as much energy in a few thousandths of a second as the Sun in 100 years. Ideally, astronomers would discover an object and focus one or more different telescopes at it, but the ephemeral nature of these bursts removes any such opportunity.

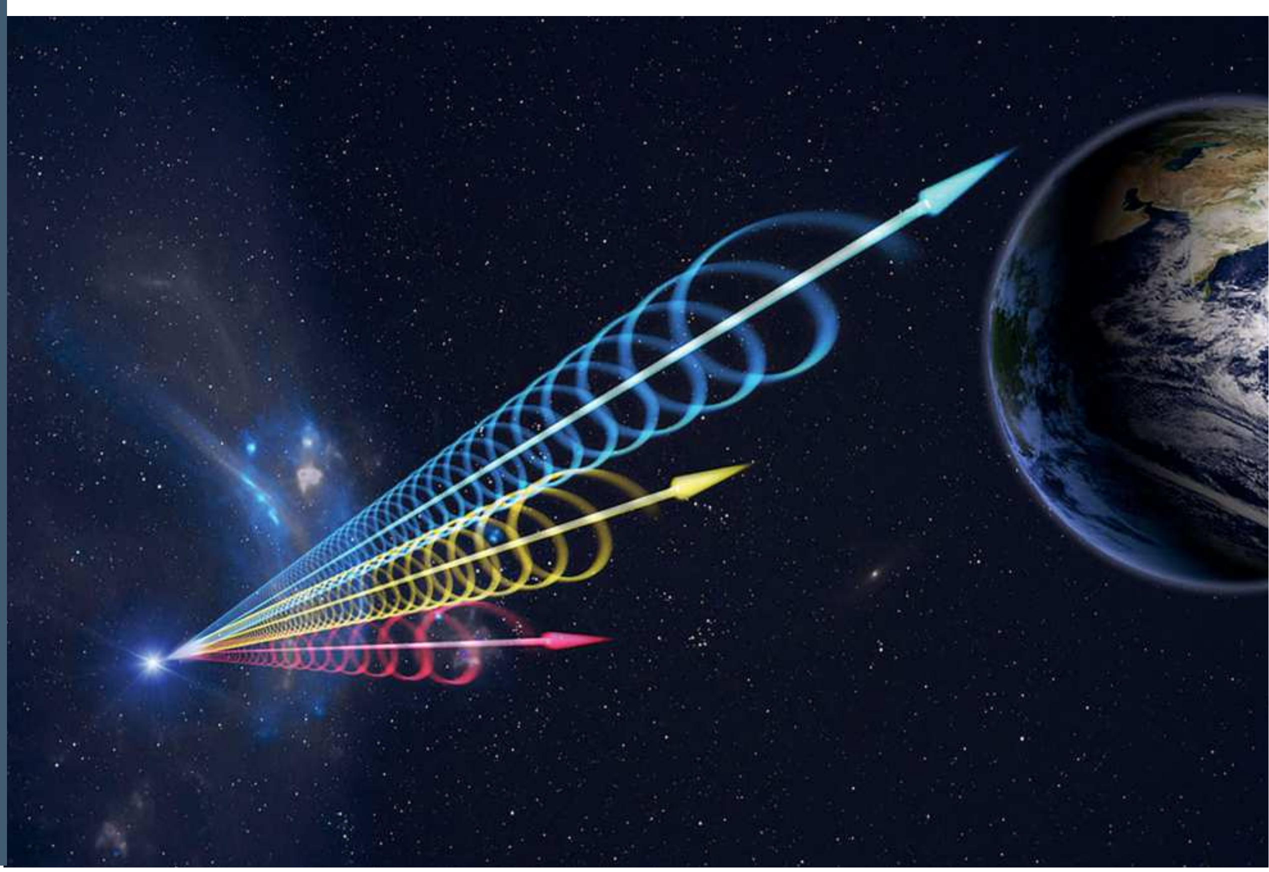
> "WE KNOW THEY COME FROM VERY SMALL SOURCES – NO MORE THAN A FEW HUNDRED KILOMETRES IN SIZE"
> KIYOSHI MASUI

Even so, despite these challenges, astronomers have succeeded in building up a bank of knowledge about FRBs, most of which has been based on the dozens of recorded events from beyond our own galaxy. For starters, we know they are bright flashes of radio light lasting for microseconds to milliseconds. "All-sky searches for them also suggest that thousands of these bursts occur in the sky every day," Chawla adds.

We also know that most of them come from billions of light years away. But while dozens of models have been proposed to explain the origins of FRBs, with progenitors ranging from neutron stars to white dwarfs to cosmic strings, have any theories really prevailed? "Well, we know that they come from very small sources – no more than a few hundred kilometres in size," says Masui. "And the most likely sources are neutron stars since they are both very small and very energetic."

Certainly, the FRB discovered in the Milky Way is allowing astronomers to firm up such theories, and it's become something of a breakthrough for scientists trying to get to the bottom of what is causing them.

Thanks to some nifty cosmic detective work involving the data of other telescopes monitoring the same patch of sky, observational evidence is now suggesting that the origin of FRBs is very



likely a magnetar – a type of young neutron star born from the embers of supernovae with a magnetic field 5,000 trillion times more powerful than Earth's, thereby making them the universe's most powerful magnets.

But how has this conclusion been drawn? To explain, we must consider the work that has gone into studying FRBs in relation to magnetars, which are known to emit high-energy electromagnetic radiation, notably gamma rays and X-rays. Both of these erupt in short-lived flares, and there has been speculation that radio waves could be emitted in such a process that would pinpoint magnetars as the source for FRBs.

When this latest FRB was discovered in our galaxy – known by astronomers as FRB 200428 – it was found to have originated in the constellation of Vulpecula, which just so happens to be where the galactic magnetar SGR 1935+2154 is located. It was also accompanied by a burst of X-rays that further excited astronomers.

The first detection of X-rays from that sky region came the day before CHIME and STARE2 discovered FRB 200428. The Neil Gehrels Swift Observatory and the Fermi Gamma-ray Space Telescope detected multiple X-ray and gamma-ray bursts coming from SGR 1935+2154 which was known to exhibit transient radio pulsations.

Other telescopes were also found to have observed an X-ray burst from SGR 1935+2154 – crucially, at the same time of the fast radio burst. These included the Konus-Wind detector on board NASA's GGS-Wind spacecraft and the European Space Agency's INTEGRAL space telescope, both picking up an X-ray burst at the moment CHIME and STARE2 recorded the FRB.

For another check, attention turned to the Five-hundred-meter Aperture Spherical Radio Telescope (FAST) located in southwest China. This fixed-diameter dish telescope was found to have detected a fast radio burst in the direction of FRB 200428 and it put its location somewhere around SGR 1935+2154, which further cemented the association between the X-ray source and fast radio bursts. The latter was comparable to other FRBs found outside the Milky Way, adding to the body of evidence.

"What this means is that the FRB came from the direction of a known magnetar within our galaxy and the radio burst happened at exactly the same time as an X-ray burst coming from the same magnetar," says Masui. "It's a clue as to how magnetars produce FRBs, but the community is still trying to work out what it all means."

What has become clear is that FRB 200428 is the first observed fast radio burst to send out emissions other than radio waves, and scientists have benefitted hugely from having discovered an FRB so close to home. The detection of the X-ray

© Jingchuan Yu, Beijing Planetarium

## HOW CHIME IS USED TO DISCOVER FAST RADIO BURSTS

Located in Okanagan Falls, the Canadian Hydrogen Intensity Mapping Experiment picked up on FRB 200428

### 1 Collecting radio signals

There are no moving parts in the CHIME radio telescope. Instead, as the Earth turns, radio waves emitted by celestial objects are received from a narrow stretch of sky that runs from the northern to southern horizons.

### 2 Cylindrical reflectors

The radio waves are collected by four semi-cylindrical parabolic reflectors aligned north to south, each one measuring 20 metres (66 feet) by 100 metres (328 feet) and lined up in a row. With the northern sky scanned east-west every 24 hours, this gives a 200- square-degree field of view.

### 3 Focal assembly

Radiation is received by 256 dual-polarisation antennae that are lined up above the reflectors and spaced 30 centimetres (12 inches) apart. They are sensitive from 400 to 800 MHz in both linear polarisations.

### 4 Processing the data

Each microsecond of data results in 2,048 amplified analog samples being processed by an electronic system called the F-Engine, which is safely housed inside two shielded six-metre (20-foot) shipping containers. The signals are digitised and then converted into a 1,024-element frequency spectrum.

### 5 Spacial correlation

The data is sent by optical cable to the GPU-based X-Engine housed in two shielded 12-metre (40-foot) shipping containers. It's a 1,000-processor high-performance cluster that can figure where the signals are coming from and create an accurate sky map.



© Nicholas Forder

# THE DIY APPROACH TO SPACE DISCOVERY

STARE2's trio of radio detectors were cobbled together by a student using household items


© Caltech

### 1 A DIY approach

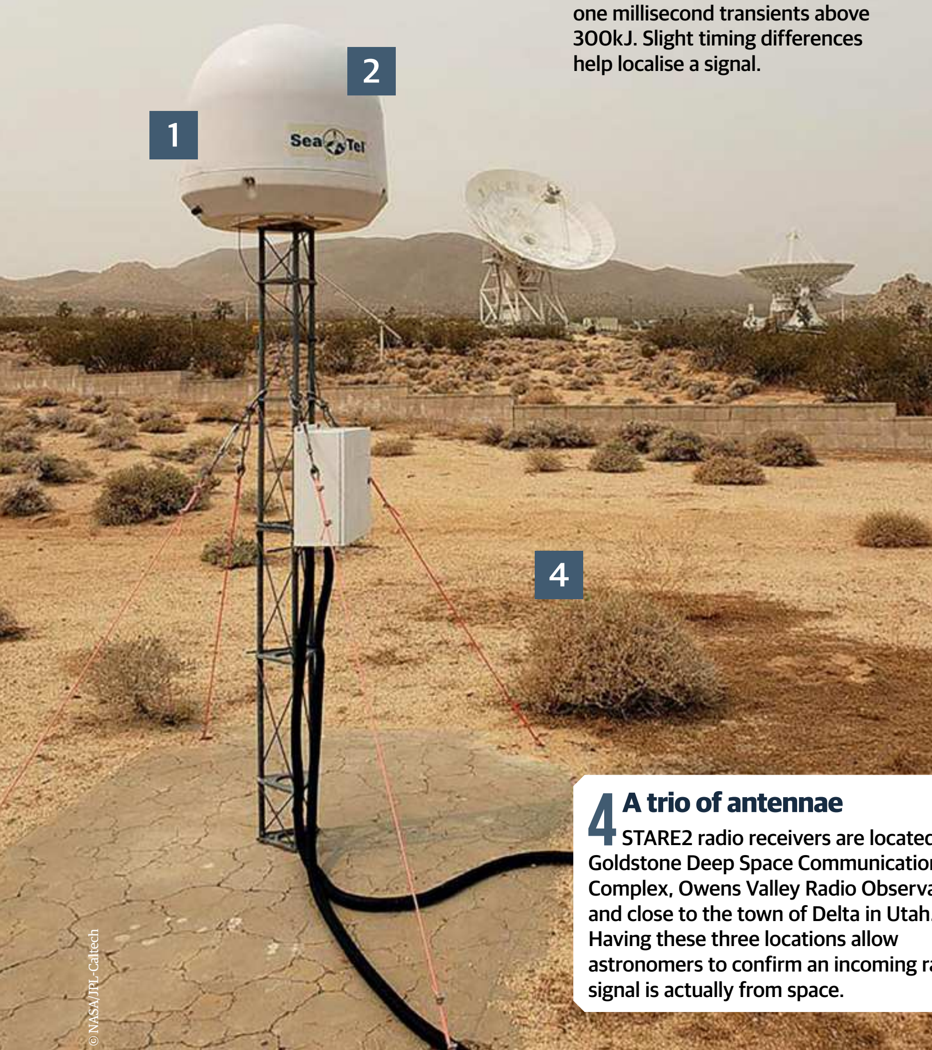
Each antenna is bucket-sized and made from a 15-centimetre (six-inch) piece of metal pipe. This is surrounded by a couple of cake tins that help adjust the instrument's sensitivity. It works like a car antenna.

### 2 Shielding from interference

The system was built for $15,000 (£11,000) by CalTech student Christopher Bochenek. He even used his Toyota Prius car – which emits radio waves – to test an instrument designed to block unwanted interference.

### 3 Coverage of the sky

The antennae form a triangle that also enables them to cover the whole visible sky. Combined, STARE2 has a field of view of 3.6 steradians and it's sensitive to one millisecond transients above 300kJ. Slight timing differences help localise a signal.

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### 4 A trio of antennae

STARE2 radio receivers are located at Goldstone Deep Space Communications Complex, Owens Valley Radio Observatory, and close to the town of Delta in Utah. Having these three locations allow astronomers to confirm an incoming radio signal is actually from space.

burst at the same time as the radio burst confirmed a magnetar as the origin, and it's the evidence astronomers have been looking for.

"The discovery of an FRB in our galactic neighbourhood is significant because the proximity makes it a lot easier to follow up the source with telescopes observing at other wavelengths," says Chawla. "None of the FRBs ever discovered have been known to emit at any other wavelengths, and this is the first detection of an FRB at a different wavelength. These observations can probe the source environment in greater detail, providing clues about the origin of FRBs."

CHIME in particular has proven to be an essential tool. Based at the Dominion Radio Astrophysical Observatory in Canada, it's a novel radio telescope with no moving parts and it has a high mapping speed thanks to its 200-square-degree field of view and broad frequency range of between 400MHz and 800MHz.

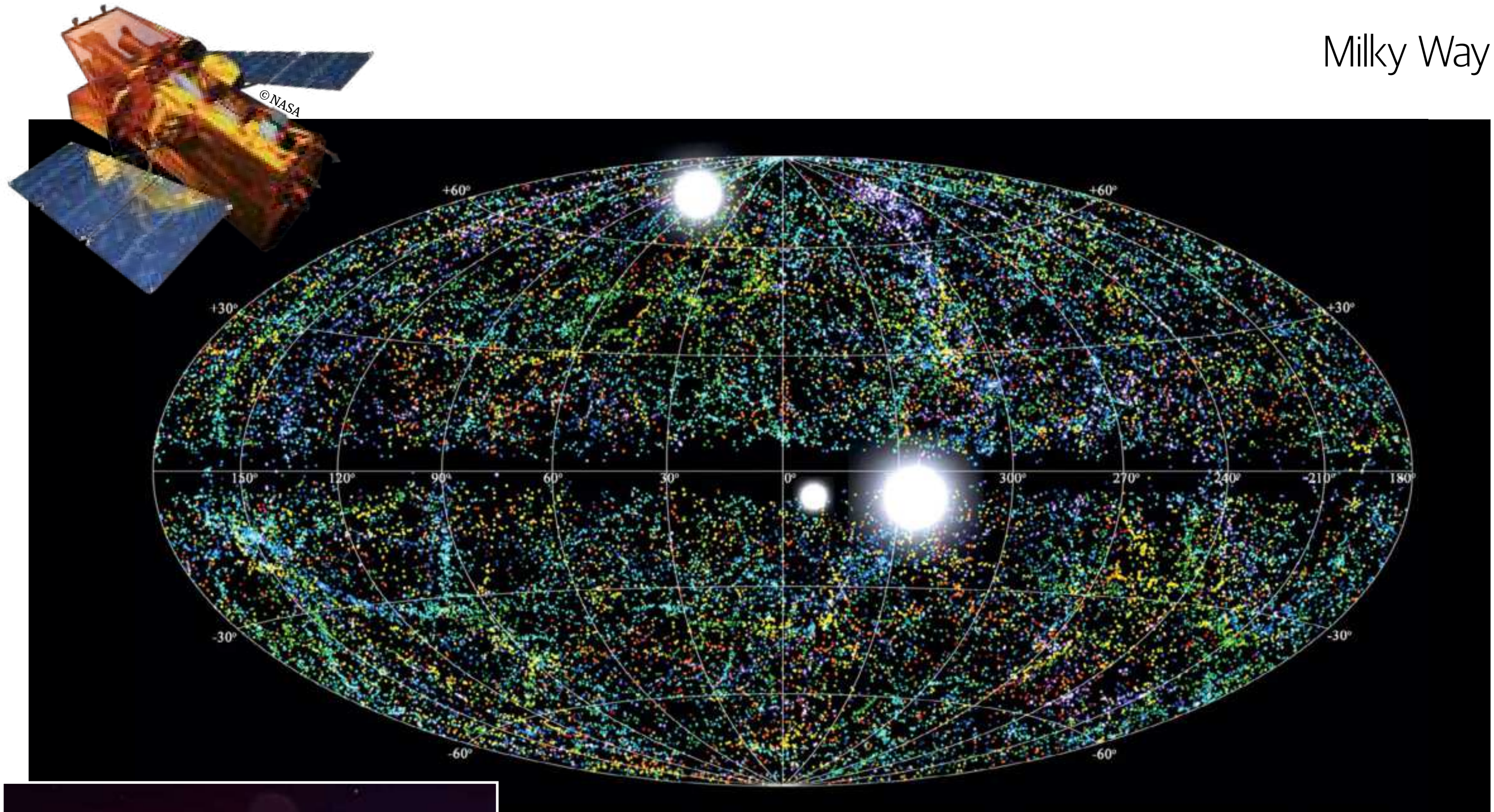
"Most radio telescopes aren't able to pinpoint the location of an FRB well enough to associate it with a known object. Those that are able to localise FRBs with great precision usually look at small patches of sky and can only observe a patch of sky about the size of the full Moon. They are not able to monitor several known magnetars at once," says Chawla.

"CHIME, however, observes an area about 500-times larger and it can therefore monitor all magnetars located in the northern sky every day, allowing us to detect a burst as rare as this one. It combines its localisation capabilities with the large sky area, and that has allowed us to both detect this burst and associate it with a known object."

It's certainly been revolutionary, and it's fast become the main observer of FRBs, with a correlator supercomputer processing 13 terabits of raw data per second to produce a radio map of the sky. "Our ability to detect far-off FRBs has improved dramatically over the past few years," says Masui. "Between 2007 and 2017 roughly 50 FRBs were detected. In the last two years, CHIME has seen several hundred. This is possible because of CHIME's digitally driven design, where the light is focused using digital signal processing, making it able to see large swathes of the sky at once." And yet the case is not entirely closed on this mystery.

As Chawla tells us, young, extragalactic magnetars form only one of the proposed models of FRBs. Bursts from known magnetars in our own galaxy have never been observed to be as powerful as extragalactic ones, and, for the purposes of the study into FRB 200428, astronomers inferred that the burst they detected was 3,000-times brighter than any burst previously observed, thereby making the magnetar model for FRBs more plausible.

"The burst we saw was still less energetic than most extragalactic FRBs, so we cannot say for sure whether magnetars can explain all FRBs," Chawla says of a burst that was a thousandth of the energy of any equivalent found outside the Milky Way.



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> "IT'S BEEN SUSPECTED FOR SOME TIME THAT MAGNETARS MIGHT BE THE SOURCES OF FRBS"
>
> KIYOSHI MASUI

It may well be the case that weaker bursts are more prevalent and it's simply a matter of this one being close enough to detect. But when it comes to pinning the source of FRBs on magnetars, astronomers need to remember that they come in two guises: those that have repeating signals, which means they frequently generate the outbursts over and over again, and others that, like FRB 200428, generate more infrequently.

It could be the case that infrequent FRBs are caused by magnetars and the frequent ones are caused by a different phenomena. On the flip side, it could also mean that two types of magnetars may exist, causing the two different types of fast radio bursts, or even that the brightest FRBs are caused by objects other than magnetars. Only further research will shed light on the answer, since all we can really say for sure is that we know at least some fraction of FRBs come from magnetars

"It's been suspected for some time that magnetars might be the sources of FRBs, but this confirms it for at least some fraction of them since we've seen it happen once," Masui says. "But we still don't know how magnetars create them – we know the 'what' and next is the 'how': how do magnetars do it?"

As such, it remains important to discover what powers an FRB to emit such energy – perhaps electrons interacting with magnetic fields creating an 'engine' of sorts. "We would be interested in determining how extreme the properties of these magnetars need to be to allow a burst from it to be seen across the universe," says Chawla. "But the most interesting application of FRBs would be to use them as cosmological probes to study the distributions of electrons and magnetic fields in the universe with unprecedented detail."

Astronomers will also continue to look at how X-ray emissions and these bright bursts of energy are able to occur at the same time. "Whether or not all FRBs are created through the same mechanism is an outstanding question, and it's subject to much debate among astronomers," concludes Masui. Given that, it's clear astronomers will be delving into the ongoing mystery of fast radio bursts for some time.

**David Crookes**
*Science and technology journalist*
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.

**Top:** The Neil Gehrels Swift Observatory was the first spacecraft to detect activity from the galactic magnetar SGR 1935+2154, on 27 April 2020

**Above:** An illustration of how fast radio bursts appear randomly across the sky

**Right:** Astronomers were astonished to discover that, as well as firing off an X-ray burst, SGR 1935+2154 also sent out an extremely brief pulse of radio waves

## A MYSTERY SOLVED?

The detection of an FRB in our galaxy has led astronomers to conclude such bursts involve a magnetar

**At long last, astronomers can now say with great certainty that fast radio bursts, or FRBs, have a magnetar as their source. It had long been theorised that these dead magnetic stars – spinning remnants resulting from the explosion of a massive star – were a potential source. But only now, with the discovery of FRB 200428, has there been firm evidence for such a theory. Being able to place this FRB in the same area of sky as magnetar SGR 1935+2154 was the breakthrough needed, particularly when an X-ray burst occurred simultaneously. Now astronomers will work to find out if magnetars are behind every FRB.**

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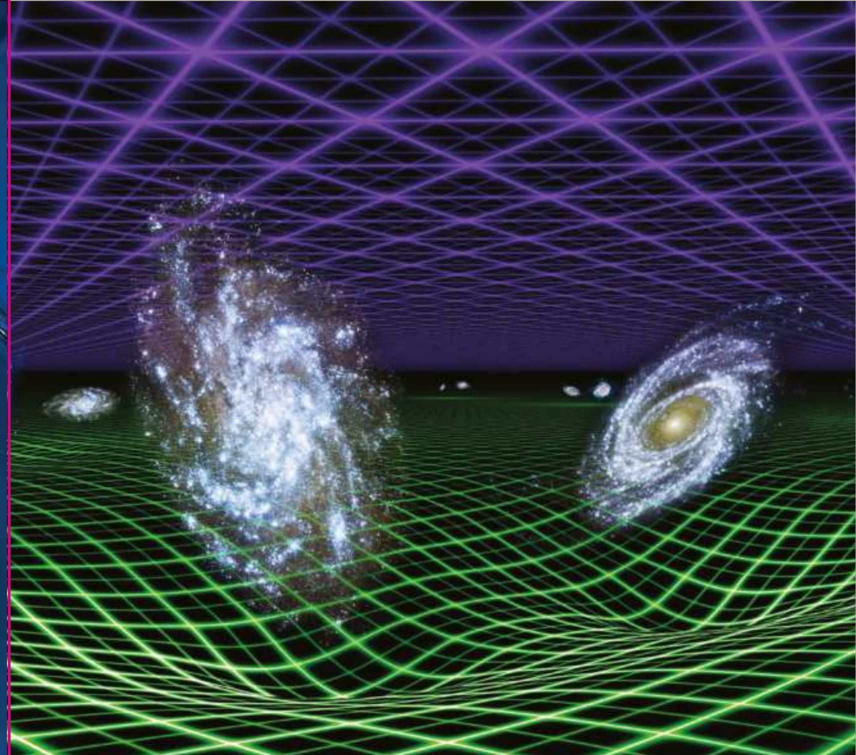
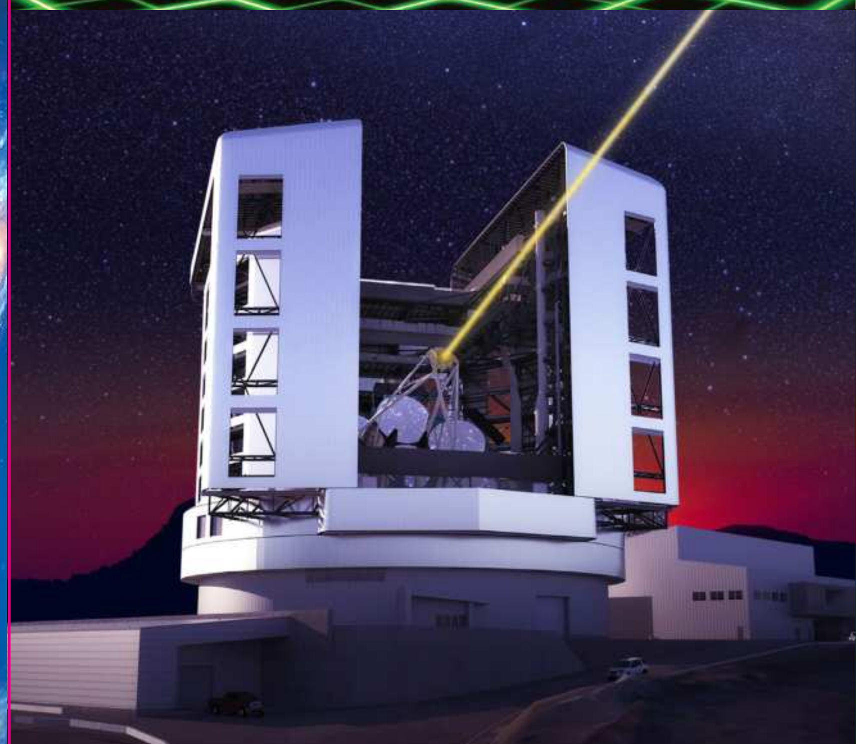
# Space Science

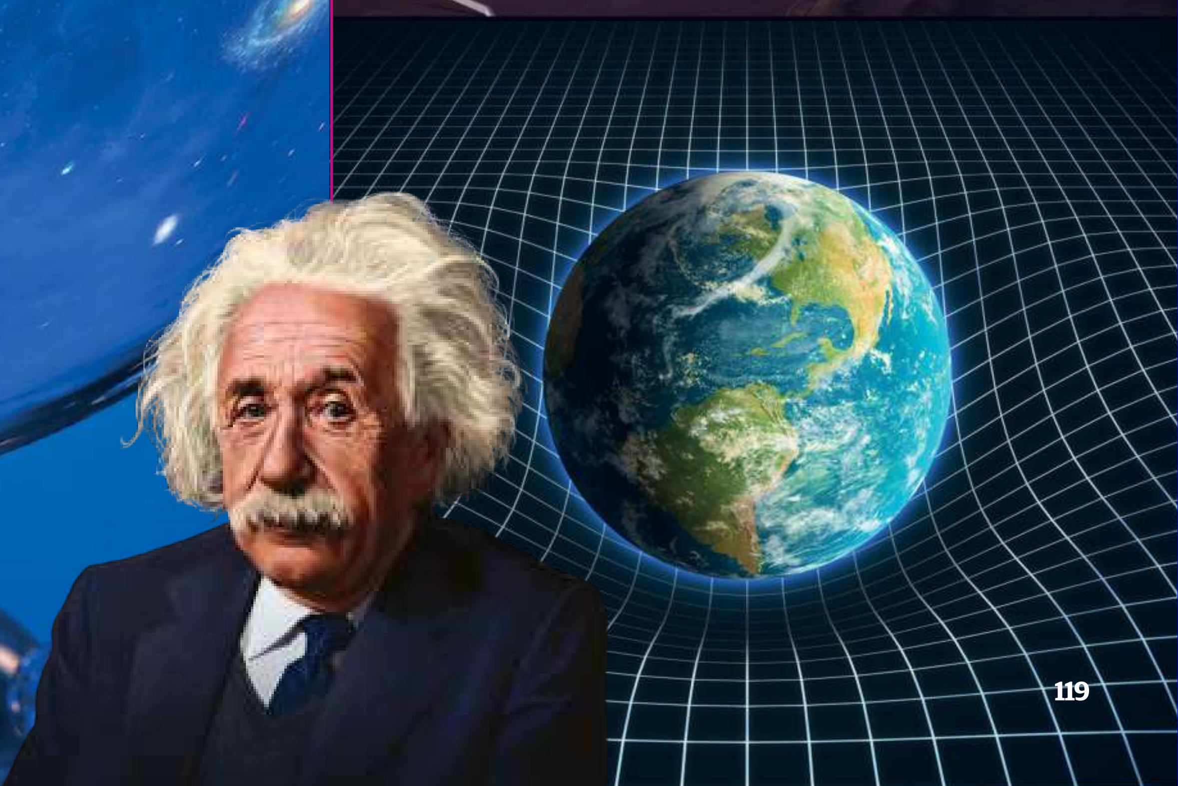
## Discover intergalactic theories and understand the science of space



"Increasingly there is also talk of 'dark' or 'modified' gravity"







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# SHEDDING LIGHT ON PHANTOM ENERGY

## AND THE DARK SIDE OF THE UNIVERSE

**Understanding the 'undetectable' cosmos could well lead to significant changes in some highly cherished theories that govern space-time**

Reported by Paul Cockburn

We live in an age of precision cosmology. As we continue to observe and study the universe around us using ever more precise instruments and increasingly sophisticated data-processing systems, the findings have invariably proven to be unexpected - if not frankly bizarre. Perhaps the most famous of these findings was the gradual realisation that everything we can see in the universe - every dust cloud, asteroid field, planet, star, nebula and galaxy cluster - simply doesn't have sufficient mass to ensure that the universe behaves in the way it clearly does - at least according to the standard model of cosmology, grounded in Einstein's general theory of relativity.

A potential solution to this problem was first suggested as far back as the early 1930s with dark matter, so called because it must consist of a material that neither emits nor reacts with visible light - or indeed any part of the electromagnetic spectrum. And so the dark side of the universe was born.

More recently - albeit indirectly by detecting its gravitational influence - astronomers have learned more about dark matter, not least the astounding fact that it must make up around 23 per cent of the total mass in the universe. Nevertheless, once dark matter is added to Einstein's theory, it fits everything from star formation to the fact that galaxies don't simply fly apart due to their rate of spin.

But it is not just about dark matter. In 1929 observations made by Edwin Hubble revealed that the universe appeared to be expanding - that most galaxies were moving away from us, and that those which were furthest away were doing so the fastest. The correlation between the distance and speed at which the universe is expanding was soon dubbed the Hubble

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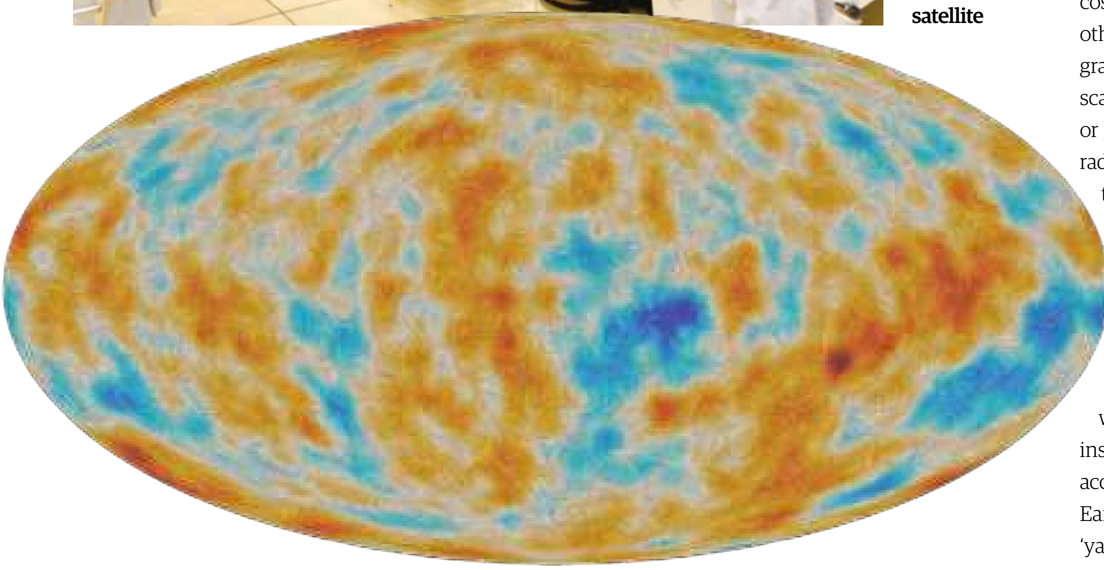
“DISTANCES BETWEEN COSMIC OBJECTS ARE LIKELY TO DOUBLE IN ANOTHER 9.8 BILLION YEARS”

**Left:** The European Space Agency’s (ESA) Planck Observatory measured the cosmic microwave background radiation of the cosmos

**Below:** A snapshot of the oldest light in the universe, as seen by the ESA’s Planck satellite



constant, but don’t let that name fool you – as it turns out, it’s neither constant nor unchanging as the universe expands!

When it came to what was causing this expansion, astronomers eventually opted for the idea of dark energy as a solution – an unknown form of energy permeating all space which ensures matter increasingly repulses matter. Again, for Einstein’s theory to work, this dark energy needs to account for more than two thirds – about 73 per cent – of the energy in the universe, a proportion that might strike some as wishful thinking.

Nevertheless, in more recent decades, indirect evidence has been found that supports the idea of dark energy, not least when astronomers compare distance measurements and their relation to the redshift in the light detected from the objects. The fact that the universe appears to have expanded more in the latter half of its life is one such example of evidence in favour of dark energy. Dark energy may well explain why, going by measurements taken of the direction patterns in the cosmic microwave background (CMB), it appears the universe is close to being flat, which would only be possible if some form of unknown energy existed to balance its overall density against an otherwise insufficient amount of mass – matter and dark matter combined – in the universe.

However, dark matter and dark energy now appear insufficient to keep the standard model of cosmology perfectly in sync with how the actual universe is observed to work. Cosmologists are increasingly talking of ‘dark radiation’ and a specific form of dark energy that’s been dubbed ‘phantom energy’. This astronomical phantom energy is not to be confused with the phantom energy – or ‘vampire energy’ – drawn by electrical equipment from the grid when switched off but still plugged in.

Increasingly there is also talk of ‘dark’ or ‘modified’ gravity, a somewhat more drastic approach that suggests we simply don’t fully understand the fundamental nature of the universe and that gravity – especially at huge cosmological scales – doesn’t actually follow the rules laid down by Einstein’s general theory of relativity.

Robert Caldwell is a theoretical physicist at Dartmouth College, New Hampshire, whose research focuses on addressing questions about the basic properties of the universe. “I guess they’ve really only been discussed since about 2000,” he explains. “Dark energy and dark gravity are both proposals to explain the significantly accelerating cosmic expansion, which can’t be explained otherwise. Some people have suggested that maybe gravity has a different description on cosmological scales, so that goes under the name of modified or dark gravity – I kind of like ‘dark gravity’. Dark radiation – that’s a funny one. I guess really where that comes in is the gap between the ‘allowed’ amount of radiation in the early universe and the amount we can account for.”

A recent spur for talking about these newer aspects of a ‘dark’ universe was a scientific paper, published in June 2016, written by Adam Riess of Johns Hopkins University, along with the support of 14 coauthors from 11 research institutions around the globe. Based on the most accurate calculations of the distances between Earth and 19 different galaxies – relying on the ‘yardsticks’ of more than 2,000 variable Cepheid stars and Type 1a supernovae – the paper’s findings were startling. According to the study, the revised speed of the expansion of the universe is 73.2 kilometres (45.5 miles) per second for every 3.26 million light years – that is, every 3.26 million light years further away we look, we find the universe is expanding 73.2 kilometres (45.5 miles) per second faster. At this rate, distances between cosmic objects are likely to double in another 9.8 billion years.

The challenge this refined figure poses, however, is that it doesn’t fit the expansion rate predicted from wider measurements made of the afterglow from the Big Bang – the cosmic microwave background – as measured by the European Space Agency’s Planck satellite. In fact, the difference is three to four times the ‘uncertainty’ factored into the latest figures.

Simply put, the paper suggests that the universe is currently expanding some nine per cent faster than it should be, at least according to the astronomers’ predictions. “Either something else

# PHANTOM ENERGY AND THE EXPANSION OF THE UNIVERSE

This mysterious form of dark energy could very well cause our cosmos to end by being torn apart



### 1 The Big Bang

Some 13.8 billion years ago, the universe began in a rapid expansion that originated from an area of high temperatures and high density.

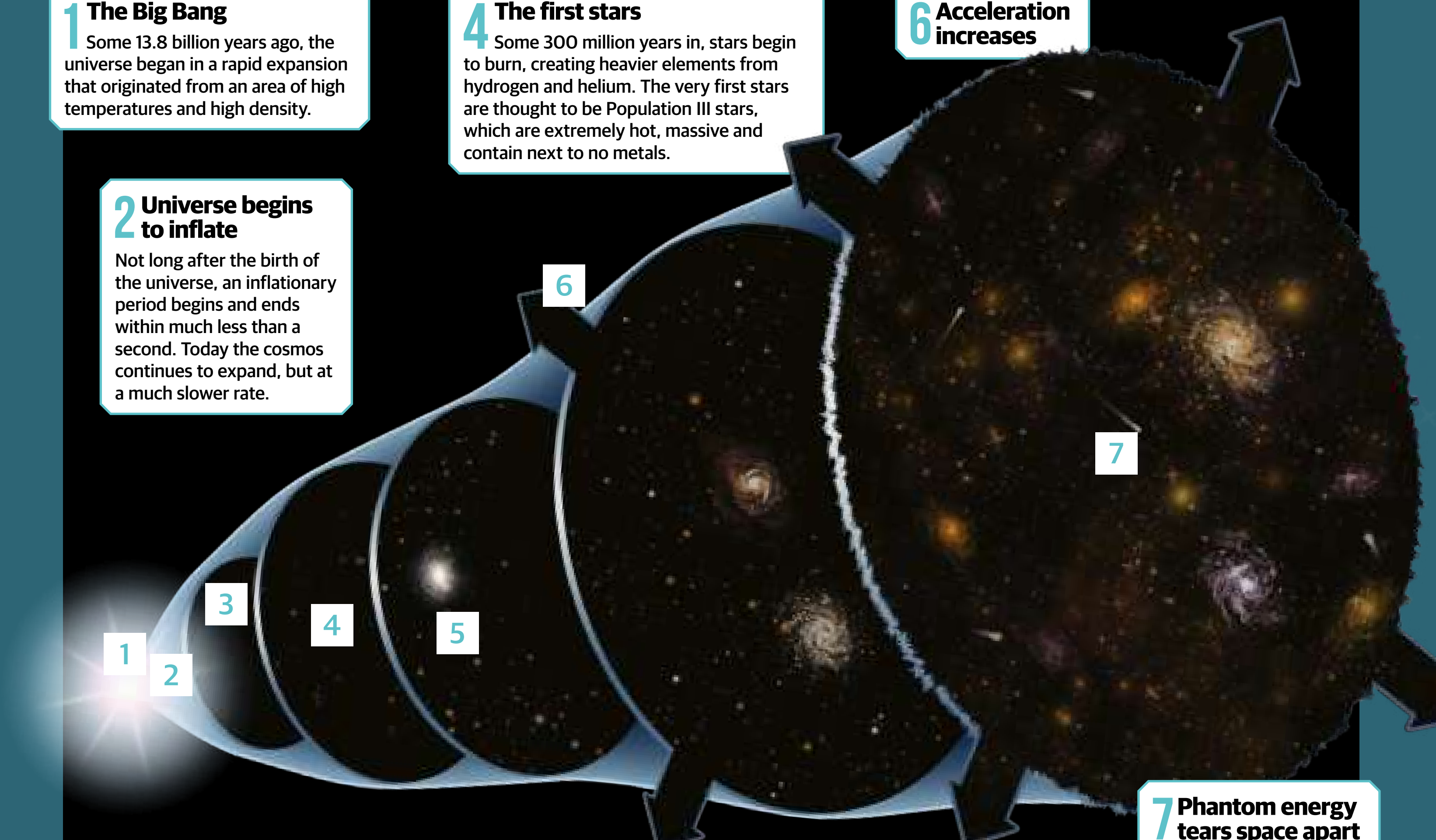
### 2 Universe begins to inflate

Not long after the birth of the universe, an inflationary period begins and ends within much less than a second. Today the cosmos continues to expand, but at a much slower rate.

### 4 The first stars

Some 300 million years in, stars begin to burn, creating heavier elements from hydrogen and helium. The very first stars are thought to be Population III stars, which are extremely hot, massive and contain next to no metals.

### 6 Acceleration increases




### 3 The Dark Ages

For 150 million years the universe is transparent, without any large-scale structures. During this time the only real radiation was the so-called hydrogen line – when there's a change in the energy state of the neutral hydrogen atoms.

### 5 Galaxies are made

Large volumes of matter collapse to form galaxies. The very first galaxies are thought to have been well in place some 400 million years after the Big Bang. These young galaxies coalesced with others to form giant galactic structures.

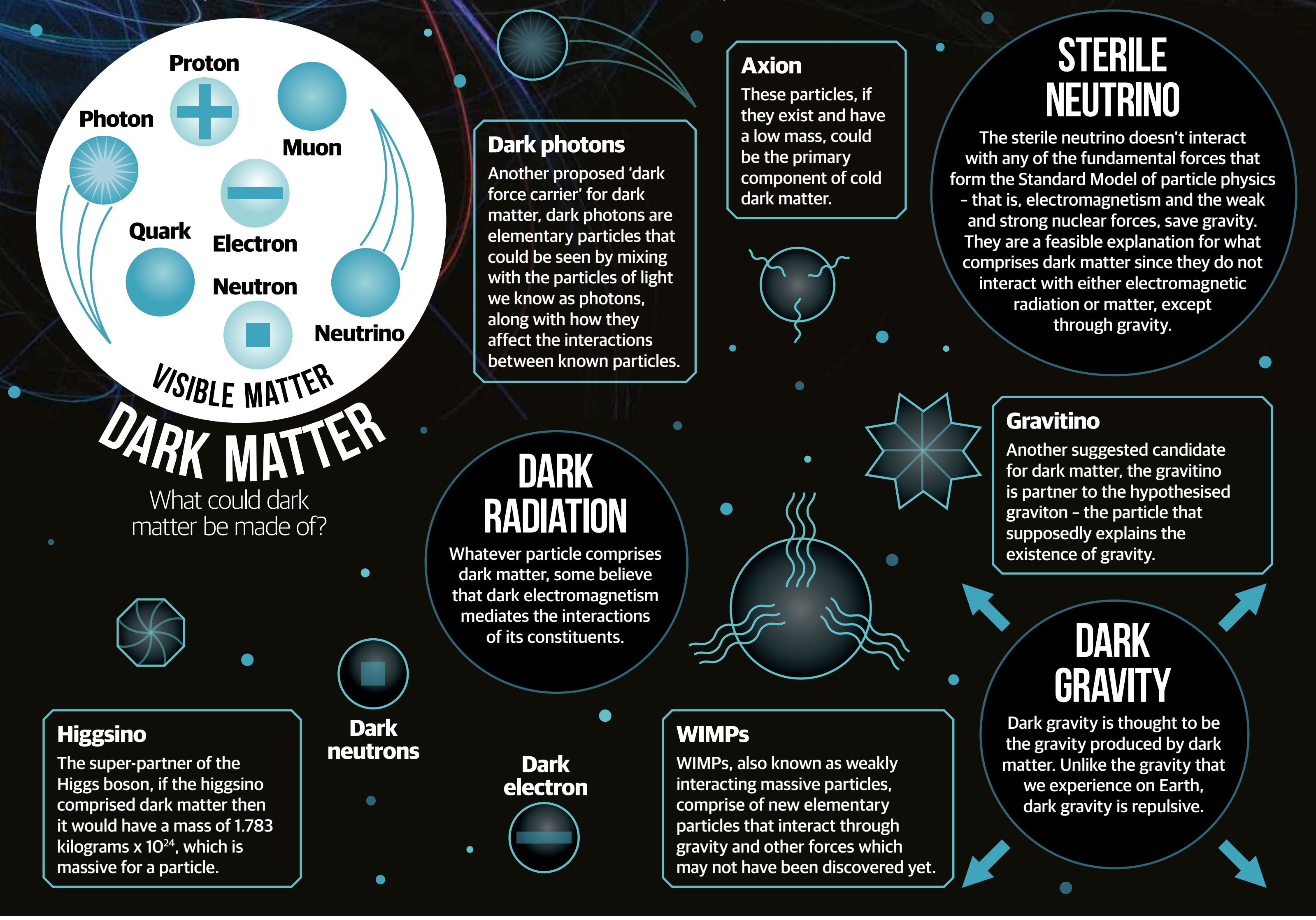
### 7 Phantom energy tears space apart

Some scientists believe that phantom dark energy – a hypothetical form of dark energy – will cause space-time to accelerate beyond the speed of light, leading to the universe ending in a Big Rip.

**Right:** Some 8,000 galaxies ensure the Shapley Supercluster is the largest structure in our 'local' universe

# DARK MATTER'S RADIATION AND GRAVITY

Whatever comprises dark matter, even darker elements could be responsible for its behaviour




is missing, as in there's a new type of substance we don't know, or the things we already know of are really weird and crazy and something funny is going on," explains one of the paper's authors, Dr Brad Tucker from the Mount Stromlo Observatory at the Australian National University. "We either add in something new or we really have to figure out what we think about dark matter and dark energy and what they are."

"While there have been published doubts raised about the accuracy of some of this CMB data, taken at face value it appears we may not have the right understanding, and it changes how big the Hubble constant should be today," Riess said at the time. "This surprising finding may be an important clue to understanding those mysterious parts of the universe that make up 95 per cent of everything and don't emit light, such as dark energy, dark matter and dark radiation." Given its breadth and scope, astronomers around the world have taken the findings of Riess and his colleagues very seriously. After all, in 2011 Riess had shared the Nobel Prize in Physics for the initial discovery that the universe wasn't just expanding, but that the rate at which it was doing so was also increasing.

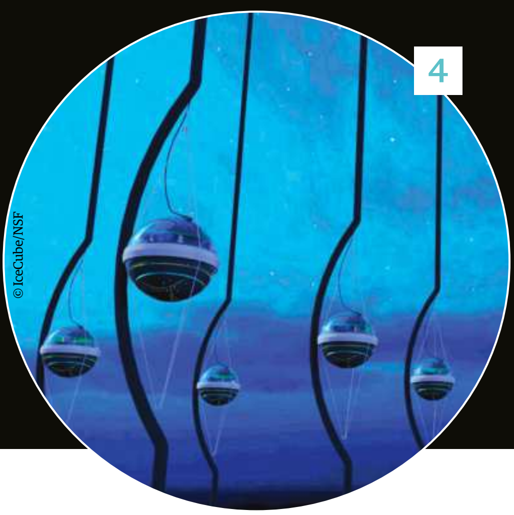
Professor Erik Verlinde of the University of Amsterdam has spent much of his time since 2010 attempting to develop a totally new theory of gravity, one that explains such observations without the need to invoke the likes of dark matter and dark energy. This resulted in his theory of 'emergent gravity', so called because gravity is not a fundamental force after all, but an 'emergent' phenomenon, similar to temperature emerging from the movement of particles. This sits somewhat better with quantum mechanics, the physics of the very small, than the general theory of relativity, the physics of the very big, which has long been a problem for those looking for a so-called 'theory of everything'. An international survey looking at the gravitational lensing caused by galaxies, published in the December 2016 issue of the *Monthly Notices of the Royal Astronomical Society*, found that Verlinde's equations could explain the observations without the need for dark matter. That was just emergent gravity's first test, however, and it's by no means over for Einstein just yet.

There is an understandable reluctance to totally let go of both Einstein's theory of gravity and the well-established data on the CMB. The former may be found to be incomplete – but that's not the same as it being wrong. It's little surprise that so many astronomers have opted for there being some unknown physical phenomenon responsible for


# THE HUNT FOR THE STERILE NEUTRINO

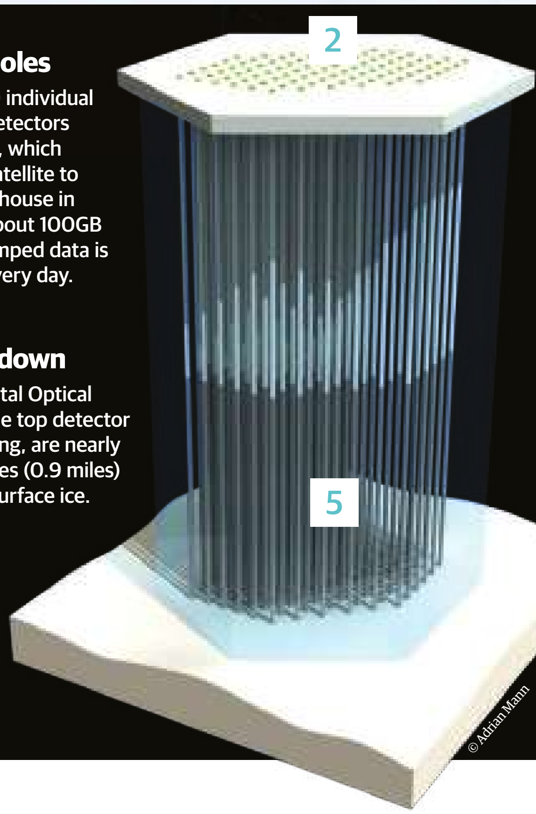
If these tiny particles exist, then the IceCube Neutrino Observatory, built under the ice of the South Pole, is one of our best chances of finding them

**1 Bedrock**
IceCube rests just above the Antarctic bedrock, hoped to help block out neutrinos from below. Buried some 2,500 metres (8,200 feet) below the surface, IceCube uses the Earth itself as a filter to block out more locally produced cosmic rays while letting neutrinos in.




**2 Boreholes**
Over 80 individual strings of detectors gather data, which is sent by satellite to a data warehouse in America. About 100GB of time-stamped data is collected every day.

**4 Deep down**
The Digital Optical Modules, the top detector on each string, are nearly 1.5 kilometres (0.9 miles) below the surface ice.




**3 IceCube Observatory**
The IceCube South Pole Neutrino Observatory is located close to the South Pole, Antarctica.

**5 Looking for a flash**
There are 60 detectors on each string, which are 17 metres (56 feet) apart. There are more than 5,000 individual detectors.

the discrepancy between theory and observations. With dark energy already assumed to be the foot on the accelerator causing the universe to expand, it's not a huge step to suggest ways in which it may actually be pushing galaxies away from each other with even greater - or increasing - strength than originally expected.

However, another idea with growing support is that this greater-than-expected expansion of the universe is down to previously undiscovered subatomic particles that, in their early history, travelled close to the speed of light. Collectively these are termed 'dark radiation' and include a proposed 'fourth flavour of neutrino', delightfully known as 'sterile neutrinos'.

What is needed, of course, is evidence. At the moment the rate of expansion of the universe is the only significant, albeit indirect, sign of dark

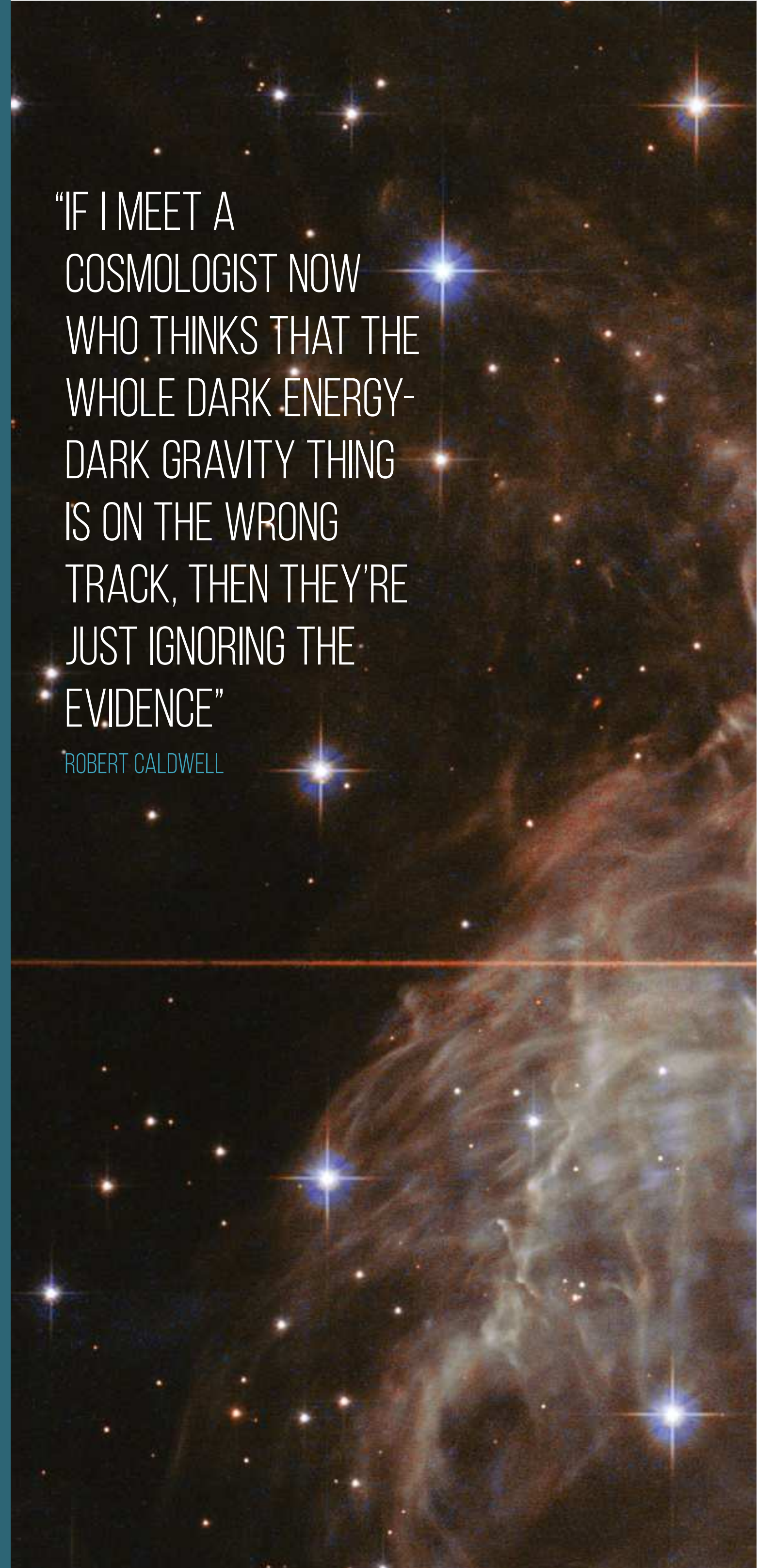

**Right:** A technician works on one of the Digital Optical Module sensors of the IceCube Observatory in a clean room

energy, and specifically phantom energy. "The rate of acceleration is greater than in other dark energy models or theories of dark energy," says Caldwell. "Usually that's expressed in terms of the equation of state of dark energy; for phantom energy the equation of state is more negative than a certain critical value. Putting together a really good measurement of the rate of expansion is the primary way that something like dark energy or phantom energy is being tested.

"Dark gravity you can begin to constrain within a particular theory, I suppose, doing the same types of tests you would for phantom energy. But if you really want to test this idea of dark gravity, you have to look at some phenomena where you'll see an appreciable difference," Caldwell continues. "In many of the theories that people have proposed, phenomena like gravitational lensing should look different in a universe described by dark gravity rather than general relativity. And so people are looking for ways to use weak lensing experiments, where instead of the lens being the Sun and the source of light being a star in the galaxy – as happened in 1919, which proved Einstein's theory correct – the lens is a cluster of galaxies and the light is much bigger."

Nevertheless, Caldwell still thinks we need to await a new idea or technological breakthrough. "The problem with a lot of these tests or theories we're going after is that in each case there's a gap and we've filled it with something," he says. "Observers are doing their duty of carrying out the measurements to the best of the technology they have and developing new techniques, pushing technology forward, but few of these theories have a unique prediction that would say: 'You just need to measure this one thing and forget the rest, and then you'll see.' That's a bit of a problem; I guess that makes it harder. We're still waiting for either that real breakthrough idea or measurement." Still, he's just as committed as most astronomers to the idea of there being these dark aspects to the universe. "If I meet a cosmologist now who thinks that the whole dark energy-dark gravity thing is on the wrong track, then they're just ignoring the evidence," he says.

But what if some aspect of dark gravity proves that Einstein simply got it wrong? "If we discover a new gravitational phenomena, then we will realise that Einstein's theory has a similar role to Newton's theory," Caldwell says. "That it's a beautiful theory that leads to testable predictions with high accuracy, but it's only valid in a certain domain, a certain range of validity – at which point it gives out to yet another theory."

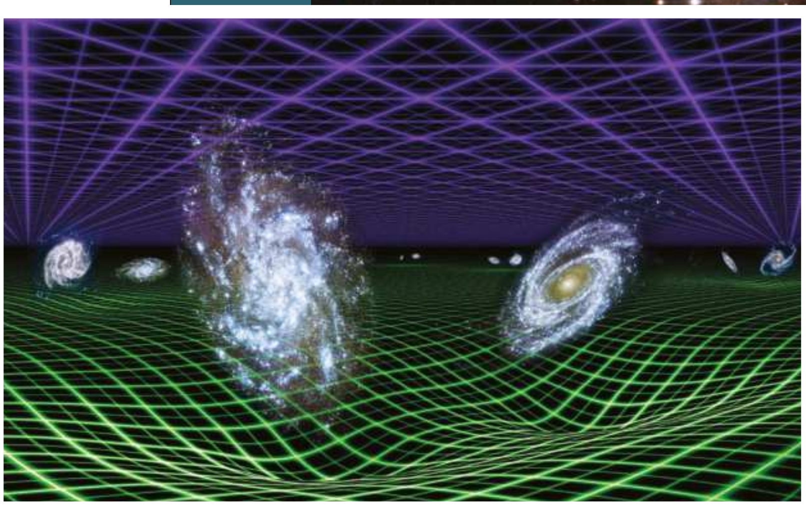


"IF I MEET A COSMOLOGIST NOW WHO THINKS THAT THE WHOLE DARK ENERGY-DARK GRAVITY THING IS ON THE WRONG TRACK, THEN THEY'RE JUST IGNORING THE EVIDENCE"

ROBERT CALDWELL

**Right:** Pulsating RS Puppis is the kind of star used to measure galactic distances

**Below:** In this artist's impression, dark energy is the smooth purple grid sitting above the galaxies





**Paul Cockburn**
*Space science journalist*
Paul has been writing about and keeping up to date with the latest research in science, technology and space for more than 25 years.

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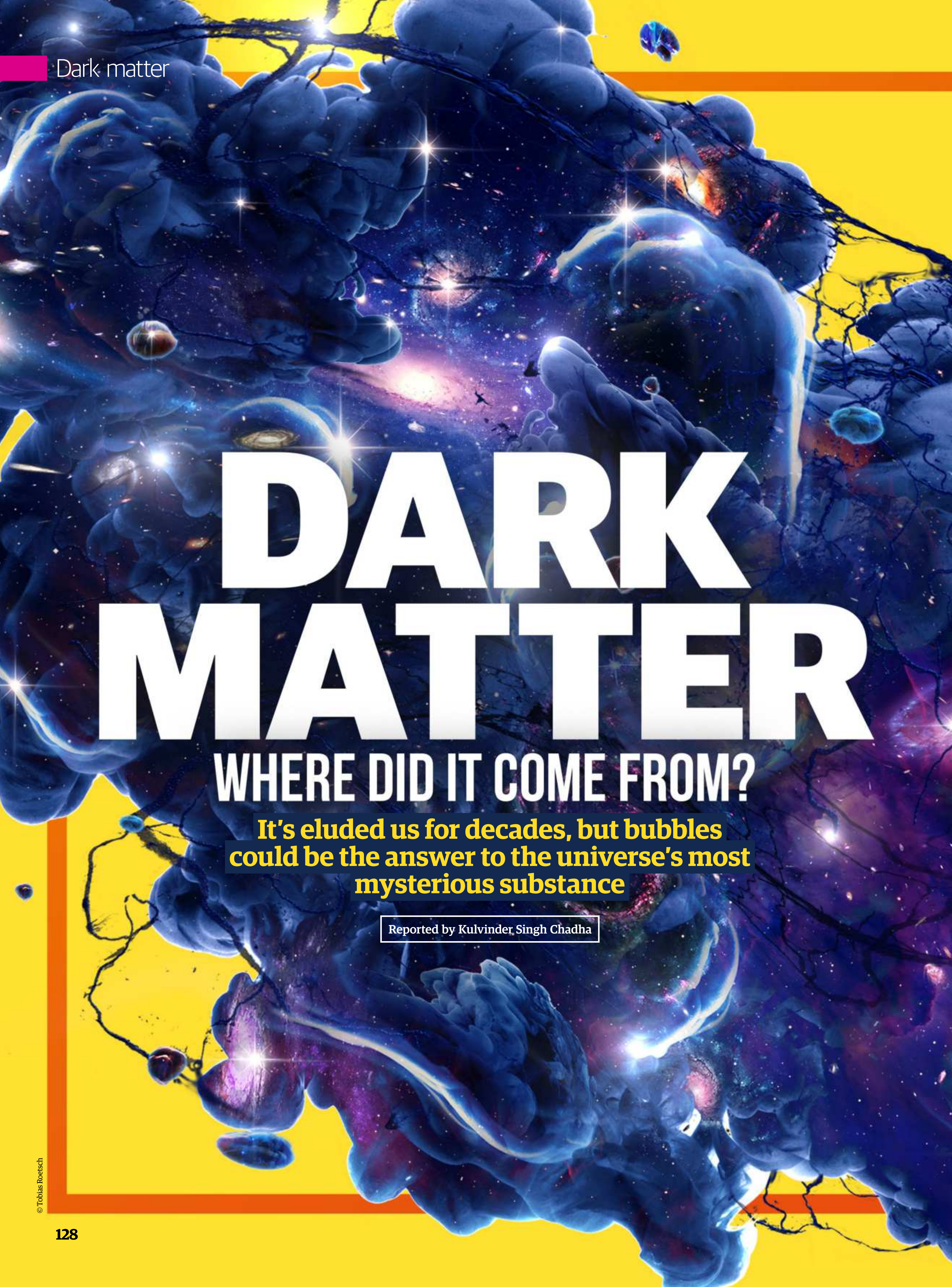


# DARK MATTER

## WHERE DID IT COME FROM?

**It's eluded us for decades, but bubbles could be the answer to the universe's most mysterious substance**

Reported by Kulvinder Singh Chadha

If something cast a shadow but you couldn't see it, you'd be intrigued. If it did that on the scale of the universe, you'd be perplexed. If you then couldn't find it despite your best efforts, you'd likely be frustrated. This is the situation that scientists looking for dark matter find themselves in. But dark matter doesn't even cast shadows; it's invisible to all electromagnetic radiation. And yet we have solid evidence that it exists. In fact, current calculations show that it comprises 80 per cent of all of the mass in the universe. Now a new study modelling dark matter as filtering through bubbles after the Big Bang may help point scientists in a new direction.

Although the mystery of dark matter can be traced as far back as Lord Kelvin, the modern breakthrough in research came in 1933. Fritz Zwicky was a Swiss astronomer working at the California Institute of Technology. Averaging the rotations of galaxies in the Coma Cluster, a large cluster of over a thousand galaxies, Zwicky noticed that their speeds were excessive. So much so, in fact, that the galaxies should have flown apart. There wasn't enough visible matter to gravitationally bind each galaxy together. He concluded that there must be a 'dunkle materie' - or 'dark matter' - component to them, which he calculated to be 400 times what could be seen. Modern calculations have lowered this value.

"THE PUZZLE OF DARK MATTER FORCES US TO THINK IN NEW WAYS"

MICHAEL BAKER

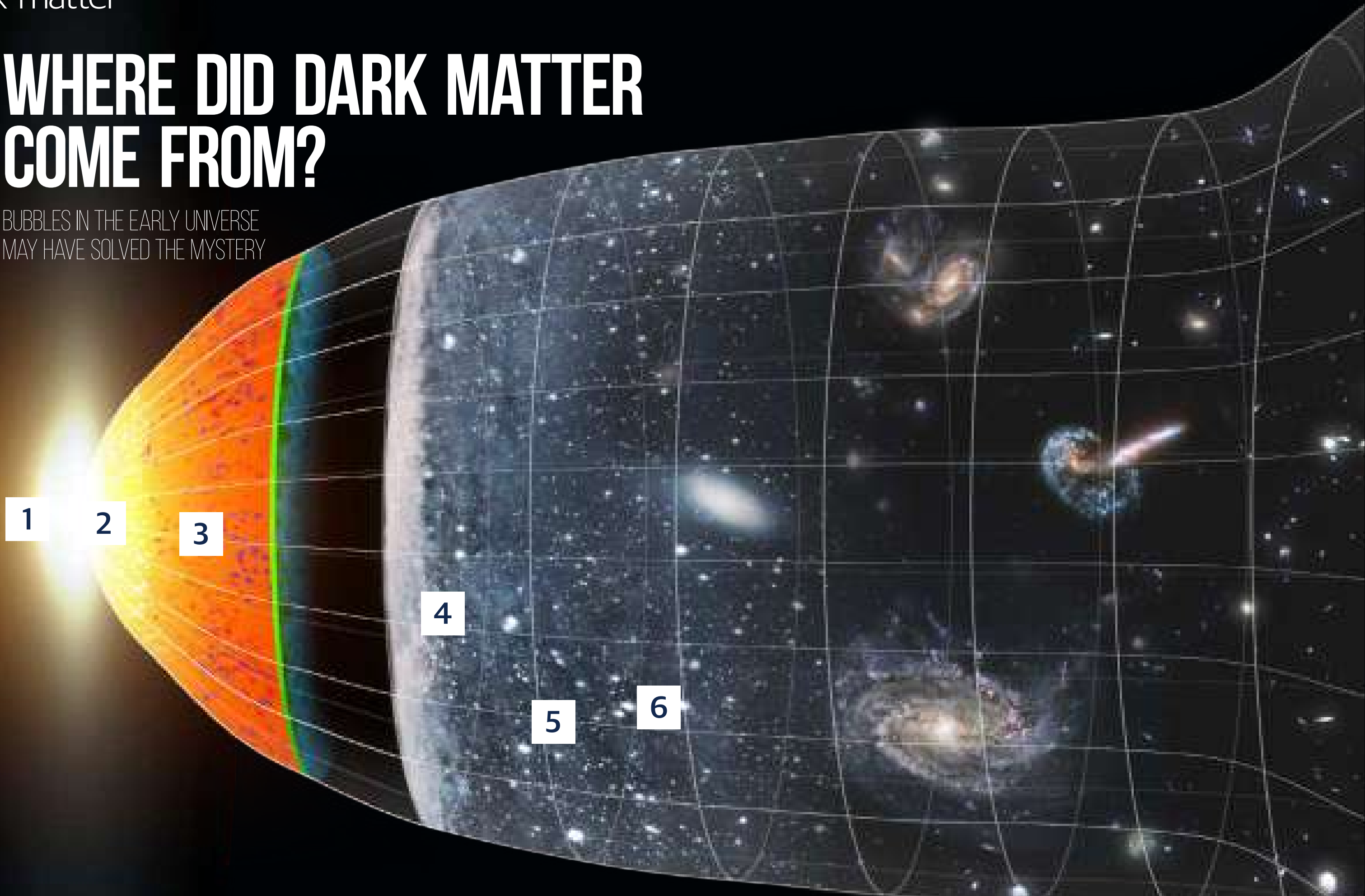
Six years later, American doctoral student Horace Babcock showed dark matter present in the Andromeda Galaxy. Curiously, it was more concentrated in the periphery of the disc than the centre. This was the first indication that galaxies had dark matter 'halos'. Then, in the late 1970s, American astronomers Vera Rubin and Kent Ford showed that galaxies contained between five and ten times more dark matter than luminous matter.

The term 'dark matter' is a slight misnomer. It isn't simply dark; it's completely invisible, no matter which part of the electromagnetic spectrum it's observed in. Its only observable effect is gravitational, much like how wind is only visible when it affects leaves, branches and hair. But this gives dark matter a dramatic quality, one predicted

**Below:** **Fritz Zwicky was the first scientist to measure the extent of dark matter in other galaxies**

# WHERE DID DARK MATTER COME FROM?

BUBBLES IN THE EARLY UNIVERSE MAY HAVE SOLVED THE MYSTERY




**1 Big Bang occurs**
The universe begins as an extremely hot, dense state.

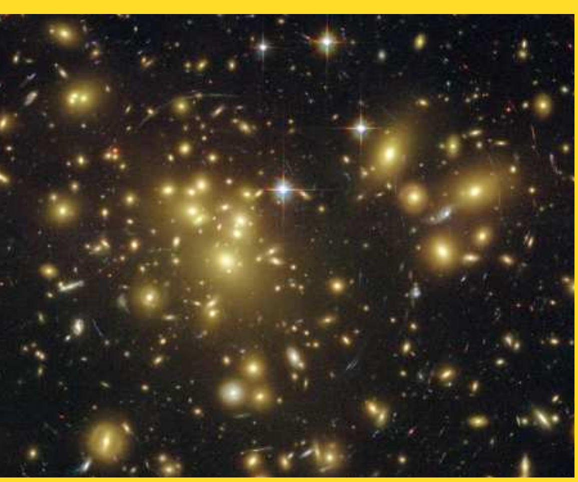
**2 Inflation happens**
At $10^{-36}$ seconds the universe expands with unimaginable speed in a period known as inflation. This cools the universe further.

**3 Thermal freeze out**
Very quickly, the subatomic particles of ordinary matter 'freeze' out of the dense plasma as it cools. So does dark matter.

**4 Bubbles form**
A particle called phi starts a phase change in the universe. These act as nucleation sites, growing as expanding bubbles.

**5 Filtering of matter**
Despite particles freezing out, they're still hot, including dark matter. Some of the latter pass into the bubbles and gain mass.

**6 Bubbles merge**
The bubbles merge, and the phase change completes. All the surviving dark matter particles are now part of the universe.



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by Einstein and one that serves as another piece of evidence of its existence.

In 1915 Einstein presented his general theory of relativity, which models space and time – or just 'space-time' – in our universe as behaving like a stretched fabric warped by the presence of mass or energy. This warping of space-time in a mass' vicinity is the explanation for gravity. This is true of planets, stars, galaxies and entire galaxy clusters.

Multiple experiments have confirmed the theory with incredible accuracy. Although not the first to do so, in 1937 Zwicky realised the implications of Einstein's theory. The path of light would be curved by this warped space-time, meaning that whole galaxy clusters could be used as gravitational 'lenses'. It was another 42 years before this effect was observationally confirmed with the twin quasar QSO 0957+561 A/B, gravitationally lensed by the galaxy YGKOW G1. Since then gravitational lensing has become a tool to measure the extent of dark matter, such as in the galaxy cluster Abell 1689. But where did it come from? To answer that, we have to go back to the very beginning.

The universe started 13.8 billion years ago in an extremely hot, dense state, known colloquially as the Big Bang. This intense region, containing all of the energy of our entire universe, was far too hot and dense for matter to exist in any meaningful sense. There was constant creation and annihilation of particles. Then things happened very rapidly.

© Tobias Roetsch

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**Above:** The quasar and its double image QSO 0957+561, detected in 1979, proved gravitational lensing

**Bottom left:** Gravitational lensing in the Abell 1689 cluster, caused by its dark matter

Between $10^{-36}$ and $10^{-32}$ seconds after the Big Bang, in a period known as inflation, the universe expanded $10^{26}$ times. Quarks and subatomic particles formed in the subsequent fractions of a second that followed. However, it was still too hot for protons and neutrons, which comprise ordinary atomic nuclei, to form. According to a lot of scientists, as expansion continued and the temperature dropped, subatomic and dark matter particles both condensed out of the cosmos' plasma, like ice crystals forming in a cloud.

These particles are often called 'thermal relics', since they are the leftovers of a higher temperature universe. The main example of thermal relic dark matter candidates are Weakly Interacting Massive Particles (WIMPS), which have been the source of most searches for this elusive substance.

But according to a new study, an alternative scenario may have played out. Instead of freezing out of cooling plasma, dark matter may have filtered out into bubbles that formed during what's known as a phase transition, when the universe changes its state from one form to another as it continues to expand. Examples of phase transitions abound in physics, including the early universe. One everyday example is boiling water. As water boils it changes phase from liquid to gas. This change can be seen in the water itself as bubbles of vapour form before escaping. Something similar occurred fractions of a billionth of a second after the Big Bang.

In the new study, published in *Physical Review Letters*, a trio of physicists working in Australia, Switzerland, Germany and Texas propose an additional new particle called phi. "The phase transition occurs when the phi field has a non-zero value in the lowest energy configuration – like the Higgs field today," says Dr Michael Baker of the University of Melbourne. In the early universe, these phi particles acted as nucleation sites, with their associated fields expanding like bubbles. Dark matter particles that formed in the super-hot, dense 'soup' of the universe collided with the bubble walls. Many simply bounced off, but some had enough momentum to pierce through into the bubbles. As they did so they gained more mass, because the particles were able to couple more strongly to the Higgs field, responsible for the Higgs boson.

The Higgs boson was discovered by the Large Hadron Collider (LHC) in 2012 and is what gives other particles mass. Due to conservation of energy, once inside these regions, now-massive particles

# WHAT IS DARK MATTER?

It's not really 'dark', but it has some properties

**It's the majority of matter**

Invisible dark matter makes up 80 per cent of the mass in the entire universe.

**It affects light**

Because of general relativity, dark matter acts as a gravitational lens and 'bends' light.

**It could be a new particle**

Dark matter could be an undiscovered particle that hardly interacts with normal baryonic matter or radiation.

**It could be a WIMP**

Weakly Interacting Massive Particles, formed after the Big Bang, could be one explanation.

**It could be an axion**

Evidence for WIMPs is weakening, giving ground to axions as a possible alternative.

**Newton's laws may need modifying**

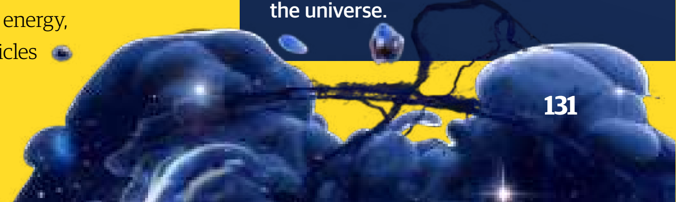
One alternative to dark matter is tweaking Newton's laws so that they behave differently at galactic edges.

**It forms the universe's structure**

Scientists think galactic clusters form in an existing 'dark matter web', forming the universe's large-scale structure.

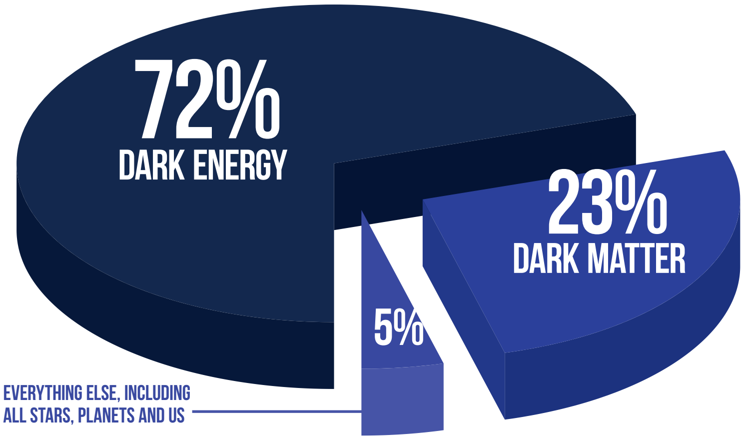
**It's long lived**

Axion dark matter could last 3,000 trillion years – roughly 220,000 times the current age of the universe.



# DARK MATTER VS DARK ENERGY

Even more mysterious than dark matter is a phenomenon in the universe called dark energy

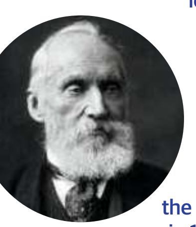



### Invisible matter

Scientists think that dark matter may be like ordinary matter, only invisible and non-interacting. However, we don't know. We could be completely mistaken, and it could be something else entirely, yet to be theorised.

### It has a gravitational effect

Like ordinary matter, its dark counterpart has a gravitationally attractive effect on its surroundings. This can be seen in the gravitational lensing of large galaxies and galaxy clusters.



### It was seen in the 19th century

Lord Kelvin first noted the peculiar motions of stars in the Galactic Centre, concluding in 1884 that a large number of 'unseen dark bodies' were present and causing the gravitational effects.

### Voyager 1 has disproved one theory

The Voyager 1 probe, now outside the Sun's heliosphere, would have been able to detect faint radiation from super-small black holes, a possible dark matter candidate. None was detected, disproving the theory.

### It's visible in the Big Bang's echo

The cosmic microwave background, the relic radiation of the early universe, can show patterns relating to matter distribution. In particular, it can show how the universe's web of dark matter evolved over time.

### It's speeding things up

In 1998, results from two separate instruments – one of which was the Hubble Space Telescope – showed that 5 billion years ago, the expansion of the universe started accelerating. The cause is labelled 'dark energy'.

### It's most of the universe

According to data from NASA's Wilkinson Microwave Anisotropy Probe spacecraft, dark energy comprises an astonishing 72 per cent of the energy density of the entire universe. Dark matter comprises 23 per cent.

### Einstein's mistake may not be wrong

Einstein's equations showed the universe was expanding when it was thought to be static. He introduced the cosmological constant to fix this. Later admitting it was a mistake, it may nonetheless explain dark energy.

### Then again, it may be

From calculations, the cosmological constant is 120 orders of magnitude too large to explain observations. Fortunately there are other models for dark energy, including a proposed new fundamental force called quintessence. But there's no evidence yet.

### We're trying to solve the mystery

The Dark Energy Survey (DES) is just one of many projects trying to uncover dark energy's secrets. In DES' case this involves mapping millions of galaxies and thousands of supernovae to see what they reveal.

**Right:** The IceCube Observatory hunts for neutrinos below the ice in Antarctica

© Rakshya Khatiwada, University of Washington

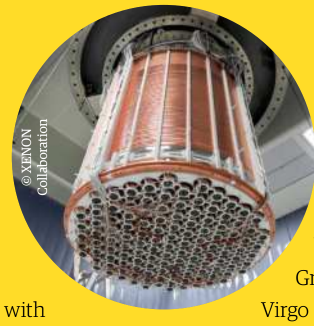
slowed down, dramatically reducing particle-antiparticle annihilations and thus cementing their place in the universe. The bubble expansions continued apace until they merged, enveloping the entire universe and leaving behind only those dark matter particles lucky enough to get in.

No one has yet been successful in detecting dark matter, so how would someone look for dark matter filtered by cosmic bubbles? "We consider the best prospects for finding evidence for our proposal are collider searches for the new [phi] particle, detection of dark matter annihilation products or detection of background gravitational waves," explains Baker. In the new study the authors state that particle-antiparticle annihilations in the galactic disc could give rise to neutrinos on the order of $10^{15}$ electronvolts. Such an event was observed by the IceCube Neutrino Observatory in Antarctica. But these events are rare, and may also come from other sources, such as supernovae.

What of colliders? In October 2020 the ATLAS collaboration at the LHC presented results using the Higgs boson itself as a tool for searching for dark matter. Rather than looking for dark matter directly, the ATLAS detector looked for signs of missing

© Adrian Mann

momentum that could indicate its presence. Nothing significant was detected, but the branching fraction – the ratio of particles decaying into another particular one – was whittled down to a maximum of 0.11 – or 11 per cent – with 95 per cent confidence.



© XENON Collaboration

As Baker points out: "We used an earlier bound of 0.19 on the Higgs branching ratio, so that constraint is now a bit stronger, although our mechanism is still perfectly viable. Note that in our case it puts a bound on the new scalar particle [phi] in our model, which is not dark matter. The fermion 'chi' is, but the scalar would behave very much like dark matter if produced in a collider." So a detection of either would be a breakthrough. Such negative results are the mainstay of dark matter physics, but they are important for ruling out lines of enquiry and chasing up more promising leads.

What about the detection of gravitational waves – ripples in the fabric of space-time – that Baker mentions? The study specifically mentions possible use of the Laser Interferometer Space Antenna (LISA), a space-borne gravitational-wave observatory using laser interferometers spaced 2.5 million kilometres (1.5 million miles) apart. Gravitational waves were first detected by the ground-based LIGO (Laser Interferometer Gravitational-Wave Observatory) and Virgo collaboration in 2015. Due to launch in 2034, early universe phase transitions are one of LISA's science goals. Due to the expansion of the universe over time, any gravitational waves resulting from bubble formation would now have a huge amplitude, necessitating LISA's large span.

And what of the dark matter itself? Could the chi particles be WIMPS, or something else? As they 'froze out' from the cosmic plasma, WIMPS would

**Left: The XENON1T experiment detected an excess signal, which currently remains unexplained**

**Right: Part of Washington University's ADMX haloscope, designed to detect dark matter axions**

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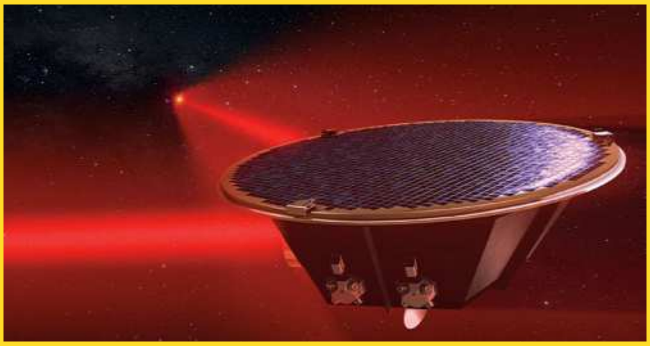
"NEGATIVE RESULTS ARE THE MAINSTAY OF DARK MATTER PHYSICS, BUT THEY RULE OUT LINES OF ENQUIRY"



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be considered thermal relics. "Most of the major current experiments are searching for dark matter based on the hypothesis that it was produced in this way," says Baker. The bubble-filtered dark matter of the new study didn't form this way, however. "Recently attention has begun to shift focus to other production mechanisms; axion dark matter is an example of a non-thermal relic that is currently actively being searched for," he says.

Axions are a hypothetical particle first proposed to explain an unusual problem in quantum physics, and are now also a possible dark matter candidate. One operation looking for them is the Axion Dark Matter Experiment (ADMX) at Washington University. Some axions are supposed to turn into microwave photons in strong magnetic fields, so ADMX consists of a microwave cavity inside a superconducting magnet, called a haloscope.

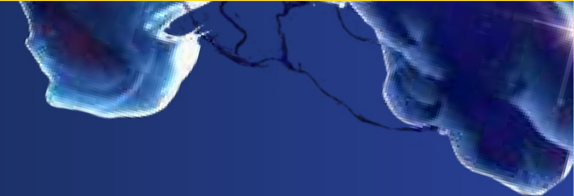
So far the international team has ruled out low-mass axions. As Professor Gray Rybka of the University of Washington says: "ADMX is currently searching masses above 3.53 microelectronvolts, and we'll let the world know if we find anything! One interesting fact is that the expected axion signal, if we find it, should be very clear." But another axion detector has already seen something, which at the time of writing remains unexplained. The XENON1T detector, operated by INFN Laboratori Nazionali del Gran Sasso, Italy, recorded an excess signal between 2016 and 2018, first published in 2020. It's possible that it's due to the presence of tritium atoms in the ultra-pure xenon used, but nothing has been ruled in or out yet.

Follow-up experiments currently underway may provide a definitive answer. Something echoed by Baker, who's looking forward to following up his own work. "The experimental landscape is quickly changing, with huge progress having been made in the last 10 to 20 years. The puzzle of dark matter forces us to think in new ways, and even if these ideas turn out to be unrelated, they could provide the key to understanding some of the deepest mysteries in the universe."

**Kulvinder Singh Chadha**
*Space science writer*
Kulvinder is a freelance science writer, outreach worker and former assistant editor of *Astronomy Now*. He holds a degree in astrophysics.

**Above:** The proposed LISA mission could detect gravitational waves from primordial phase-change bubbles

**Below:** The Coma Cluster's galactic rotation curves show the presence of large amounts of dark matter



## THE BIGGEST UNANSWERED QUESTIONS ABOUT DARK MATTER

**Is there more than one kind?**
Could there be an entire family of dark matter particles as opposed to just a single type? The Standard Model of particle physics says that ordinary matter is composed of electrons as well as the quarks that make up protons and neutrons. It also includes the fundamental force-carrying particles, such as photons, gluons, bosons and some other short-lived matter particles. Could there be a similar but separate model for dark matter?

**Are there corresponding 'dark forces'?**
Forget horror and fantasy here. If there are a range of dark matter particles, could they experience their own dark matter forces? If so, could that also sometimes affect ordinary particles? This is the hope of a collaboration working with the Super Proton Synchrotron at CERN. The team has examined billions of high-energy electrons, looking for an energy deficit in the resulting photons. The idea is that 'dark photons' would interact with normal photons and carry away some energy, thus showing themselves by their absence. Nothing's yet been detected, but the team will try again in 2021 after an upgrade.

**Could it be responsible for the universe's matter?**
In the very early universe, fractions of a second after the Big Bang, equal amounts of matter and antimatter should have been created. They then both should have annihilated one another, leaving a universe filled only with radiation. But the universe is filled with matter, with little sign of the missing antimatter. What led to this asymmetry is still one of the biggest mysteries in cosmology. Could dark matter be the culprit? The Baryon Antibaryon Symmetry Experiment at CERN is testing whether dark matter particles could interact preferentially with antimatter. This might account for the lopsidedness we see today.

**Could it already have been detected?**
The Gran Sasso National Laboratory in Italy hosts the XENON dark matter experiment, of which the XENON1T detector team announced an unexplained signal excess in June 2020. The possibility is that it could be due to contamination of the xenon by tritium, but it's not yet been confirmed. Gran Sasso also hosts the DAMA/LIBRA experiment, which looks for dark matter in the galactic halo using a different design based on scintillation crystals. This too detected unexplained signals, with seasonal variations. The results are inconclusive, but a new version called SABRE, based at Gran Sasso and Australia, may prove or disprove any known natural variations.

© NASA/ESA/Hubble Heritage Team

# DARK MATTER GALAXY DEBUNKED

## Astronomers claimed a galaxy was 98 per cent dark matter... but they were wrong

Back in 2016, researchers claimed to have found a galaxy made almost completely of dark matter. Now that claim has fallen apart. The galaxy, Dragonfly 44 (DF44), belongs to a class of mysterious objects known as ultra-diffuse galaxies, or UDGs. Researchers have debated since the 1980s whether these vast, dim objects have a low mass, like dwarf galaxies smeared across huge reaches of space, or are heavy, Milky Way-style galaxies that seem dim for two reasons: because they have almost no stars, and because a huge fraction of their mass is dark matter found in the outer fringes of the galaxy in so-called dark matter haloes that emit no light. In a paper published in 2016 in *the Astrophysical Journal Letters*, scientists argued that DF44 was one of these galaxies with a big dark matter halo and few stars. They estimated its mass and found it was at least 98 per cent dark matter.

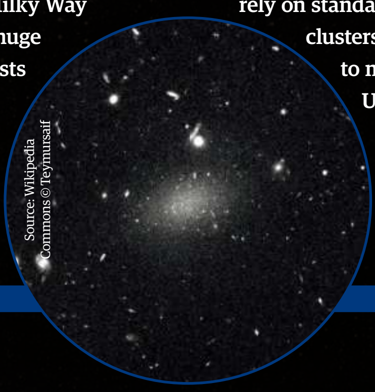
But a new analysis suggests the earlier study got it wrong. Researchers in the 2016 study assumed a bunch of mass was globbed into the dark matter halo, but the new study showed a much lower total mass, indicating DF44 is one of those low-mass dwarf galaxies spread across space with normal percentages of dark matter. DF44 is about 360 million light years from Earth, so astronomers can't directly measure its mass. Instead they rely on proxies. Features like the speed at which objects circle a galaxy can indicate how massive it really is, as more gravity would cause objects to whirl faster.

In 2016, researchers claimed DF44 had a huge halo because of how fast its globular clusters seemed to whirl around its centre. Those velocity measurements turned out to be incorrect. But that wasn't the end of the argument that DF44 had a huge amount of dark matter. That's because the galaxy did seem to host a relatively high number of globular clusters.

Researchers have found a general relationship between the number of globular clusters in a galaxy and that galaxy's mass, said the study's lead author Teymoor Saifollahi, a doctoral candidate at the University of Groningen in the Netherlands. And DF44 did seem to have more globular clusters than you'd expect for a galaxy with so few stars. Early observations estimated about 100 of these clusters, which was later narrowed down to 80 in a 2017 paper. That puts the mass of DF44 squarely in Milky Way territory – a jarring result with huge implications for how cosmologists understand the history of galaxy formation. In the new model, galaxies would be primarily dark matter objects, able to form without many stars or other luminous matter at all.

Saifollahi and his colleagues did their own count, though, landing on a much lower number: 20. That would indicate that DF44 has a normal dwarf galaxy mass – a much less exciting result. The key difference between the 2017 analysis and the 2020 analysis, Saifollahi said, has to do with where they assumed most globular clusters in DF44 were located. The 2017 team made a rough guess as to how far the clusters would orbit from the centre of the galaxy, based on standard numbers associated with dwarf galaxies, and then looked for candidates in that area. For the 2020 paper the researchers actually measured how far the clusters extended from the centre of the galaxy, and found that the stellar globs clustered much closer to DF44's centre than expected. Counting possible clusters only in that smaller area produced a smaller number.

In future studies of UDGs, Saifollahi said, scientists will have to be more careful not to rely on standard assumptions about globular clusters. He and his colleagues plan to more closely examine other UDGs that have high estimated numbers of globular clusters and see if those estimates hold up.



Source: Wikipedia Commons © Teymursaif

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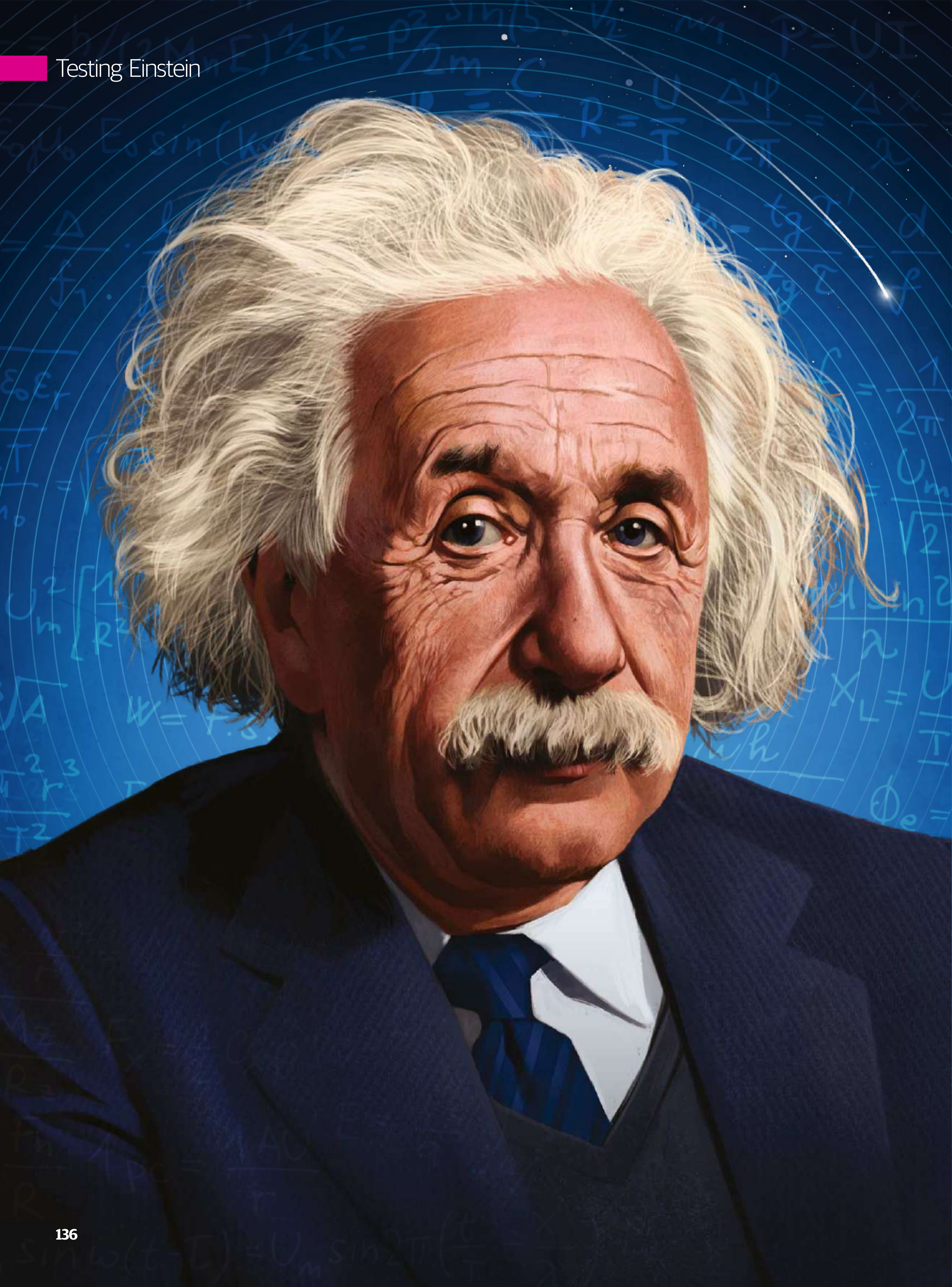


# TESTING EINSTEIN

## How attempting to break the theory of general relativity has migrated beyond the limits of the Milky Way

**Reported by Robert Lea**

Testing Einstein's geometric theory of gravity, or general relativity (GR), was never going to be a straightforward task. At the heart of GR are the effects that massive objects such as planets, stars and even entire galaxies cause on the fabric of space. Such tremendous masses aren't easily replicated in the lab, especially before the debut of complex computer simulations. In the century since its introduction, physicists have moved GR experiments into space, out past the limits of the Solar System and even beyond our galaxy.

"Space is the most ideal laboratory for testing general relativity, as its effects in and around the Solar System are so minuscule," Vivek Venkatraman Krishnan, an astrophysicist at the Max Planck Institute for Radio Astronomy, Germany, explains. "The effects of GR are significant only around objects that have strong gravitational fields - such as neutron stars and black holes - which makes them ideal laboratories for testing." During this journey, scientists have studied some of the most powerful and mysterious objects in the universe.

"GR was revolutionary because it jettisoned the Newtonian concept of gravity as an attractive force between massive bodies. It replaced it with the idea that space and time - or space-time - is warped or curved by the presence of massive bodies, and that it is this curvature that leads to the orbital motion of stars and planets and the fall of an apple from a tree," Clifford Will, professor of physics at the University of Florida and author of *Was Einstein Right?* says. "This was a strange and radical conception, and many physicists, especially experimentalists, reacted strongly against it. The main challenge was that the effects predicted in the Solar System were tiny."

Upon its introduction in 1915, Einstein knew that his new theory would have to account for the phenomena of gravity at least as well as Newton's law of universal gravitation, which had served science just fine for over 200 years. But matching its predecessor's level of experimental verification would be a challenge to say the least. To this end, the physicist calculated three tests that could be used to verify his new theory of gravity. The first of these involved doing something Newton's theory couldn't - explaining a strange 'wobble' in the orbit of Mercury.

With each orbit, Mercury's orientation shifts slightly, a movement called perihelion precession. A tiny fraction of this - just 43 seconds of arc per 100 years - couldn't be explained by the influence of

### CORRECTING MISTAKES

The original version of Einstein's theory, published in 1913, contained a mathematical miscalculation in the amount a beam of light would bend due to gravity. It was fixed for the 1915 version.

**Gravity Probe B's incredible sensitivity allowed it to test GR from an orbit around the Earth**

© NASA

# HOW DO WE TEST GENERAL RELATIVITY?

Testing the theory often means studying objects of tremendous masses only found in deep space

## MEASURING THE EFFECTS OF MASS ON SPACE-TIME

The way objects of tremendous mass 'warp' space-time can have effects on matter and energy that astronomers can see and measure. These effects can be used as a test of general relativity, as well as providing us with vital information about the physics that govern light and matter.

## 1 GRAVITATIONAL LENSING

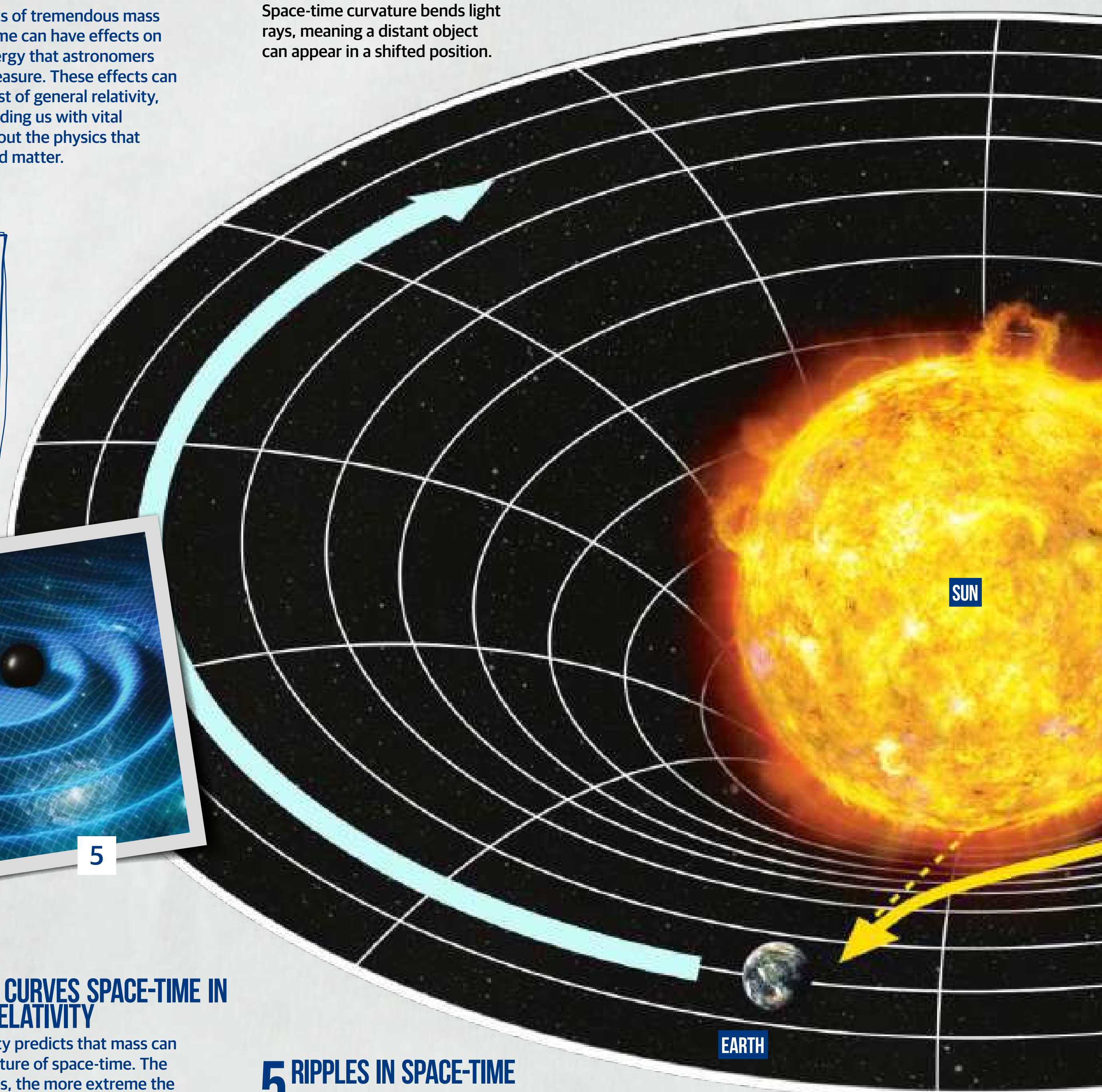
Space-time curvature bends light rays, meaning a distant object can appear in a shifted position.

## 2 EINSTEIN RINGS: GRAVITY'S ILLUSIONS

Gravitational lensing means objects can appear multiple times in the sky.

The Laser Interferometer Gravitational-Wave Observatory is able to detect ripples in space-time caused by collisions



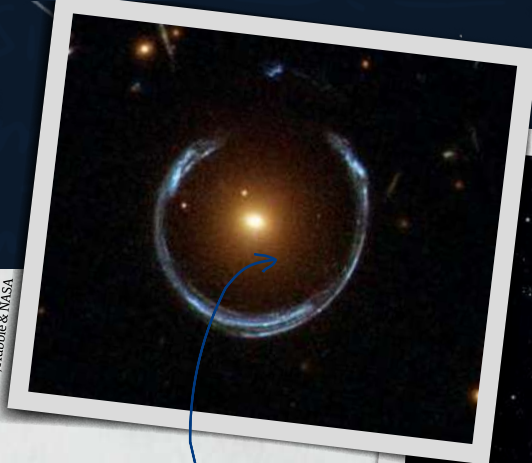




## HOW MASS CURVES SPACE-TIME IN GENERAL RELATIVITY

General relativity predicts that mass can cause the curvature of space-time. The greater the mass, the more extreme the curvature. This affects how matter and light move through space.

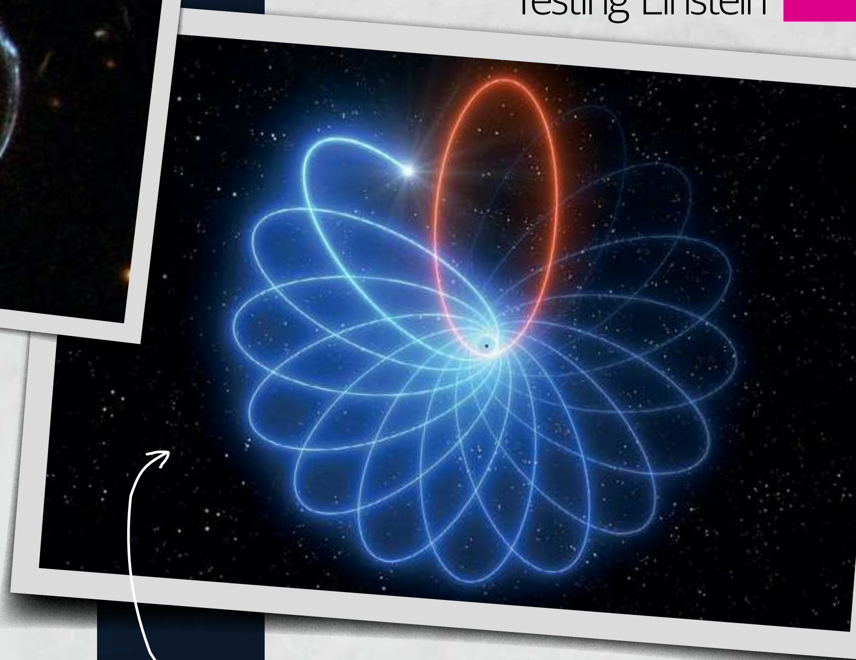
## 5 RIPPLES IN SPACE-TIME

The discovery of gravitational waves is possibly the ultimate verification of GR.





Gravitational lensing by a foreground object can divert light from more distant ones, splitting it into different sections

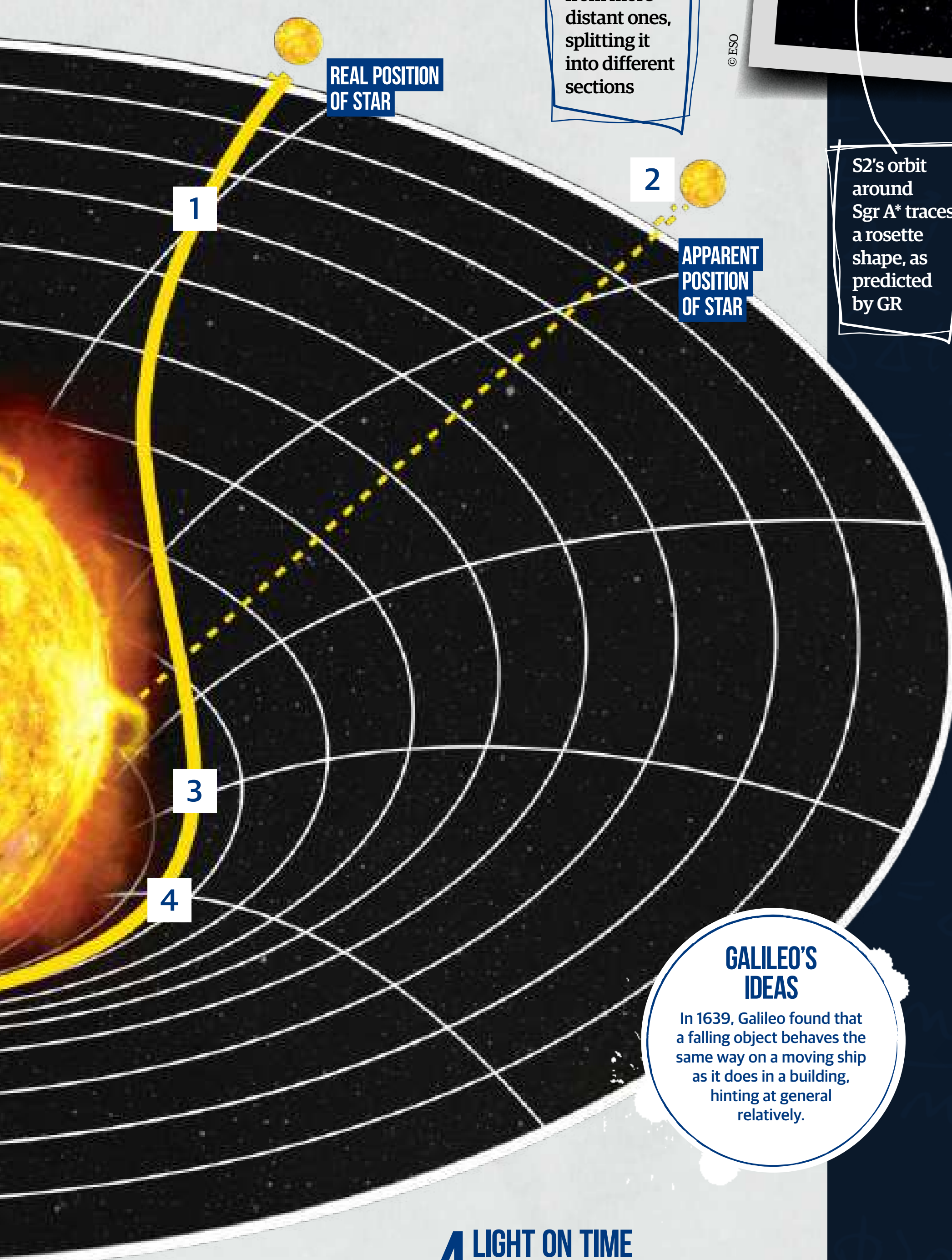




S2's orbit around Sgr A* traces a rosette shape, as predicted by GR

## 3 SEEING RED: GRAVITATIONAL REDSHIFT

Light's wavelength is 'stretched' towards the red end of the electromagnetic spectrum by the presence of mass.




other bodies in the Solar System. Einstein used an approximation of the Schwarzschild metric – a solution to the field equations underpinning the theory – to show GR predicted this perfectly.

While this was an important first step on the road to validating GR, the theory would require something bigger if it was to receive the blessing of the scientific community. "GR also predicted that light would be deflected in passing by a massive body. For the Sun, the maximum deflection was only 1.7 arcseconds, so very tiny," says Will, explaining Einstein's second test. "The only way to detect it was during a total solar eclipse."

English astronomer Arthur Eddington, one of GR's early champions, took it upon himself to perform this second test, and he and colleague Frank Watson Dyson saw the solar eclipse of 1919 as the perfect opportunity to do this. During this eclipse the cluster of stars known as the Hyades would sit behind the Sun, with some of its stars visible near the eclipsed disc. This meant that their positions could be recorded and compared to previous records, revealing any apparent shifts caused by the Sun's gravitational influence.

Eddington travelled to the island of Príncipe off the coast of west Africa to collect observations. Combined with data taken from Sobral, Brazil, by a second team, led by Andrew Crommelin from

### GALILEO'S IDEAS

In 1639, Galileo found that a falling object behaves the same way on a moving ship as it does in a building, hinting at general relatively.

## 4 LIGHT ON TIME

Massive objects cause 'Shapiro delay' – a delay in the travel time of light.

**"GR JETTISONED THE CONCEPT OF GRAVITY AS AN ATTRACTIVE FORCE" CLIFFORD WILL**

the Royal Greenwich Observatory, London, results conformed to Einstein's theory. "The announcement of the verification of GR in November 1919 made Einstein an overnight science superstar," says Will.

Despite these initial successes, the testing of GR slowed down after this, only experiencing a renaissance in the mid-20th century when the invention of equipment like radio telescopes shifted study beyond the Solar System. This renewed interest has included confirmation of Einstein's third testing criteria – the discovery of gravitational redshift. "The first test of this effect would not happen until 1960, five years after Einstein's death," Will explains. "Today, of course, the redshift effect on the clocks in GPS satellites must be accounted for, otherwise these global navigation systems would not function properly."

Moving beyond the limits of the Solar System has also made astronomical objects with far greater masses available for testing GR. "The tests of GR done within the Solar System with bodies like Mercury constitute what we call the 'weak field' regime – testing done with 'weakly gravitating' bodies," says Venkatraman Krishnan. "We have entered a brand-new regime – the so-called 'highly dynamical strong-field regime' – testing gravity around strongly gravitating bodies that are also moving at a speed that is a significant fraction of the speed of light, as is the case for colliding neutron stars and black holes that emit gravitational waves."

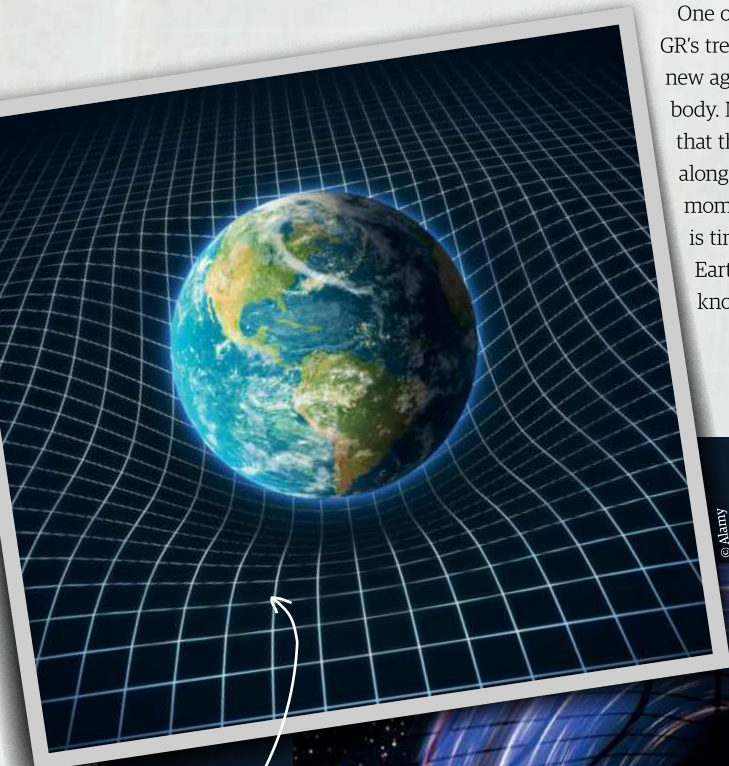
One of the most evocative consequences of GR's treatment of space-time explored in this new age occurs around a massive rotating body. Near a massive object, GR suggests that the fabric of space-time will be dragged along in the direction of the body's angular momentum. This 'frame-dragging' effect is tiny around a relatively small body like Earth. But the phenomenon – officially known as the Lense-Thirring effect – becomes much more extreme and measurable around truly massive cosmic objects like neutron stars and black holes.

"The common analogy that people use is the placement of a small ball in a bowl of honey – akin to a neutron star sitting in space-time. Add a drop of food colouring near the ball. Spin the ball quickly and notice that the honey turns with it. You will see that the ball drags the honey along, just like the rotating neutron star drags space-time," says Venkatraman Krishnan, no stranger to the Lense-Thirring effect.

The astrophysicist was part of a team that studied the dragging of space-time around the white dwarf-pulsar binary PSR J1141-6545, located in the constellation of Musca, the Fly. As well as testing GR, the experiment also allowed the team to determine the radius of the system's neutron star. As its mass is already known, this gives the researchers an idea of the density of the object. This should ultimately help researchers gather information about its composition and possibly solve long-standing mysteries about neutron stars such as their mass limits and the composition of their interiors.

## WORKING IT OUT AT WORK

**Einstein wrote much of his theory during quiet periods working at the Swiss patent office.**



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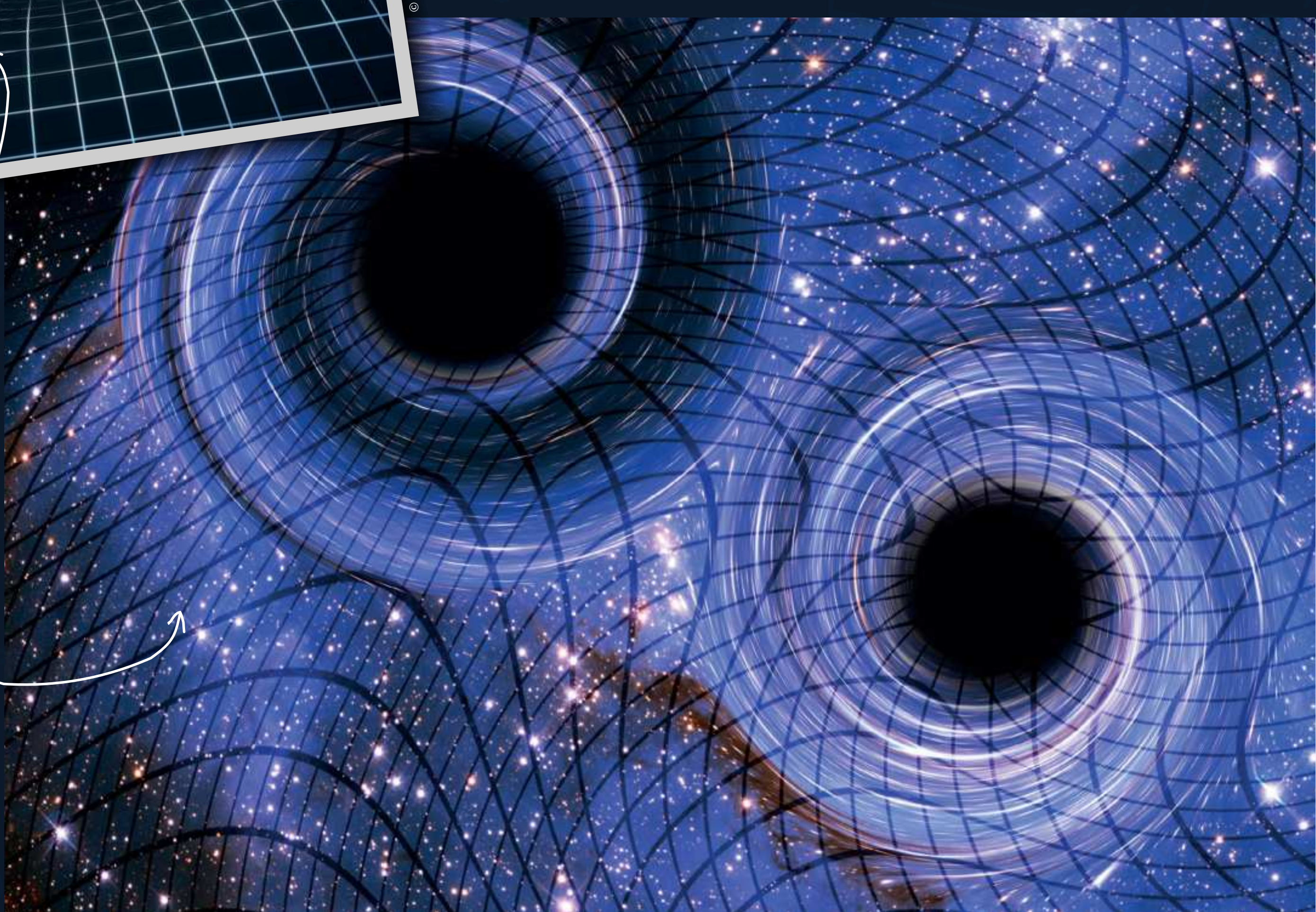
One of the most revolutionary aspects of GR was its prediction that mass curves space-time



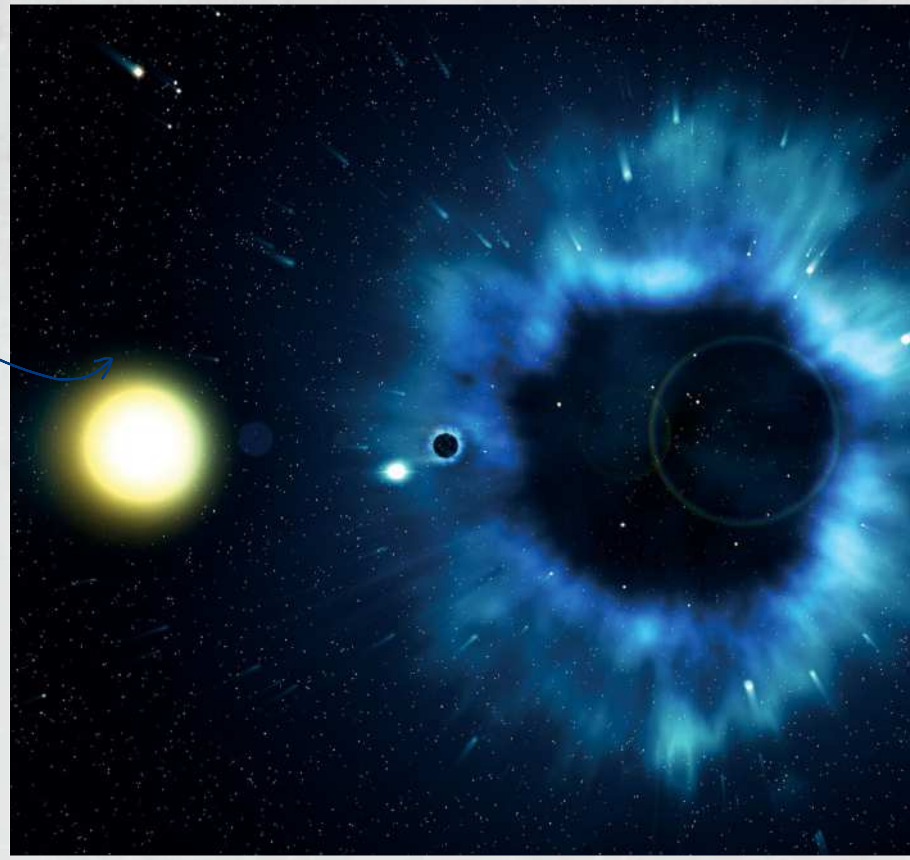
Gravitational waves from distant merging black holes are a strong confirmation of general relativity

It's no great surprise that the testing of GR – a theory of the astronomically massive – has often involved the most compact and massive space-time events possible: black holes. As they first emerged as pure theory from singularities that arose in the mathematical solutions of GR's field equations, it's only right black holes should play a vital role in the testing of the theory. The figurative shadow of the black hole may linger over GR, but it was the literal shadow of a black hole that informed a recent test of Einstein's theory.

The first direct image of a supermassive black hole (SMBH) – the one at the centre of the galaxy Messier 87 released in April 2019 – has inspired this new test of GR. Astronomers at the Event Horizon Telescope (EHT) realised that if Einstein's theory of gravity is correct, the shadow of a SMBH should have specific dimensions. The team used GR to calculate the size of the shadow of M87's SMBH, finding that its image matched these parameters. Once again this verified Einstein's theory – this time using an extragalactic object.

Closer to home – albeit still 26,000 light years away – the SMBH at the centre of the Milky Way, Sagittarius A* (Sgr A*), has played a role in modern GR tests. In 2020, a team of researchers led by Reinhard Genzel, director at the Max Planck Institute for Extraterrestrial Physics, Germany, looked for an effect similar to perihelion precession in the orbit of a star in the proximity of Sgr A*, known as the Schwarzschild precession.

**GR effects become measurable around massive objects, like this black hole with a supernova companion**



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## "SPACE IS IDEAL FOR TESTING GR; ITS EFFECTS AROUND THE SOLAR SYSTEM ARE SO MINUSCULE" VIVEK VENKATRAMAN KRISHNAN

© Getty

The team tracked S2 – one of a dense cluster of stars that resides around the bright radio source at the centre of the Milky Way – as it whipped around Sgr A* at a stunning 9 million metres (30 million feet) per second over 30 years. They observed that S2's highly elliptical 16-year orbit displayed the same open nature as that of Mercury, tracing out a rosette shape around the SMBH. Again this matched GR's predictions precisely, as well as confirming that this radio source is indeed a SMBH.

"It completely astonishes me that the theory that we are concerned with testing is precisely the theory that Einstein wrote down in late 1915," exclaims Will. "All of the other fundamental theories of physics have evolved dramatically during the same period. GR hasn't changed one iota, yet it continues to pass every single test with flying colours."

Observing the same effect first measured by Eddington and his team in the orbit of Mercury in a star orbiting a SMBH may figuratively bring GR testing full circle, but that doesn't mean physicists are done testing. The benefits of GR testing have helped unlock the secrets of neutron stars, black holes and space-time itself.

"Einstein himself did not believe several of his predictions would ever be testable. When he lived there were no lasers, and quasars and pulsars were not discovered. Now, thanks in part to GR, we use these inventions and discoveries to understand the universe better," concludes Venkatraman Krishnan. "I think we should keep testing it, pushing its limits – who knows, something entirely unexpected could be waiting to be discovered!"

**Robert Lea**
*Space science reporter*
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.

# CITIZEN SCIENCE PROJECTS TO TRY AT HOME

# HOW YOU CAN GET INVOLVED

**From classifying galaxies to identifying features on the Red Planet, All About Space reveals how you can contribute to science**

Written by Daisy Dobrijevic

If you are interested in becoming a citizen scientist there are a variety of projects that you can get involved in – depending on how 'hands-on' you want to be

Citizen science is a great way to gather and analyse large amounts of data with the aid of the general public. Collaboration between scientists and citizens has played an important role across scientific disciplines, especially in regards to space science. You don't need to have any prior knowledge to be a citizen scientist, just a willingness to participate and a desire to aid scientific discovery.

One of the most notable citizen science projects in the history of space science was Operation Moonwatch. Established in 1956 as part of the International Geophysical Year (IGY), it was the brainchild of Fred Whipple, director of the Smithsonian Astrophysical Observatory. The IGY was a worldwide effort to study Earth and its planetary environment, lasting from 1 July 1957 to 31 December 1958.

Many were sceptical about non-experts conducting research, but Operation Moonwatch soon became one of the most successful and long-running citizen science programs in history. The plan was that teams of observers around the world would track, time and document satellites passing over their location. The data would then be fed back to the computation centre and used to position Baker-Nunn cameras around the world, designed to keep an eye on low-Earth orbit (LEO) satellites.

On 4 October 1957, the launch of Sputnik 1 caught the world by surprise. Although the worldwide network of cameras wasn't ready, the thousands of Operation Moonwatch volunteers were. Suddenly the spotlight was on citizen scientists, who were the first to observe and record the trajectory of Sputnik.

Operation Moonwatch continued to play an important role in tracking and documenting satellites Sputnik and Explorer 1. After the IGY ended, teams maintained their patrol of the skies, and in September 1962 were able to provide vital information on the re-entry of Sputnik 4, which had failed to return to Earth two years earlier. Though Operation Moonwatch was disbanded in 1975, many teams continued to observe the skies, and satellite tracking is still a popular pastime for many amateur astronomers around the world. Operation Moonwatch paved the way for modern-day citizen science, having highlighted the value of collaborative research between the general public and scientists. Nowadays participation in citizen science projects couldn't be more straightforward, with many easily accessible from home on your computer or even an app on your mobile phone.

LEVEL 1 LOW-INPUT PROJECTS

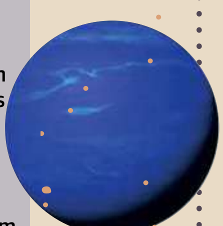
# BOINC PROJECTS

BOINC.BERKELEY.EDU


One of the most popular platforms for 'hands-off' research is Berkeley Open Infrastructure for Network Computing (BOINC). Here you can view numerous computing projects that span the sciences, taking part in any number of available projects. BOINC simply runs on your computer: once the initial set up is complete, the platform downloads scientific computing jobs and runs them invisibly in the background when connected to the internet. A majority of the projects are available for Windows, Linux and Apple macOS computers, with some also available for Android devices.

Even though you participate in these projects on your own, with your computer doing all the work, the BOINC projects still have a good sense of community. There are news bulletins, message boards and even a 'user of the day' announcement, all of which make you feel like you are part of something special.

If you don't have that much time to dedicate to citizen science, but you still want to contribute to scientific research, then these projects are the ones for you. The only time you really need to devote to them is the initial set up. After that you can simply sit back, relax and let your computer do all the hard work for you. Who knew contributing to scientific discoveries could be so easy?



## SPACE-RELATED BOINC PROJECTS INCLUDE

### UNIVERSE@HOME

UNIVERSEATHOME.PL

**Sponsor:** University of Warsaw

Contribute to the understanding of the universe with Universe@Home, the first project of its kind based in Poland. The current topics investigated by Universe@Home include ultraluminous X-ray sources, gravitational waves and Type Ia supernovae. All of the results from the research are publicly available, and there are currently over 28,000 computers registered on the project.

### ASTEROIDS@HOME

ASTEROIDSATHOME.NET

**Sponsor:** Charles University

There's a large disparity between the number of asteroids we have discovered and those with known physical properties. Asteroids@home aims to rectify this problem by deriving shape and spin for a significant portion of the known asteroid population. The results not only contribute to our scientific understanding, but are also made available to the public in the DAMIT database.

### EINSTEIN@HOME

EINSTEINATHOME.ORG

**Sponsor: University of Wisconsin-Milwaukee, Max Planck Institute for Gravitational Physics**

With over 500,000 volunteers and counting, Einstein@Home is a big name. It uses your computer's idle time to search for faint astrophysical signals from pulsars. Its main goal is to make the first detections of gravitational-wave emissions from spinning neutron stars.

### SETI@HOME

SETIATHOME.BERKELEY.EDU

**Sponsor: University of California, Berkeley**

SETI@home works to analyse radio telescope data in the Search for Extraterrestrial Intelligence (SETI). This project has been so successful that on 31 March 2020 SETI@home was put into hibernation, as the project has currently analysed all the data researchers need for now. The team behind SETI@home is now completing the back-end analysis of results and writing up scientific papers. You can continue to keep up to date with the progress by visiting the news column on the home page, as well as the message boards.

### MILKYWAY@HOME

MILKYWAY.CS.RPI.EDU

**Sponsor:** **Rensselaer Polytechnic Institute**

By harnessing the computational power of volunteers, Milkyway@home is busy building a highly accurate three-dimensional model of the Milky Way using data collected from the Sloan Digital Sky Survey.

# LEVEL 2 MEDIUM-INPUT PROJECTS

If you would like to take part in research which requires a little more input from you, but is still not too time consuming, then these are the projects for you.

## ZOONIVERSE

**ZOONIVERSE.ORG**

The world's largest platform for citizen science, Zooniverse projects have contributed to new discoveries, accessible datasets and multiple scientific publications. You don't need to have any specialist knowledge to take part, as each Zooniverse project gives you a brief introduction to the research area and clear step-by-step instructions for the task at hand. The projects are designed to be accessible to all, with ample opportunities to ask for help and discuss the projects with other volunteers around the world.

Zooniverse projects span many research areas, from sociology to biology and languages to the arts. With each project, you can see how many volunteers are involved and how complete the project is. There are also mobile-friendly projects that can be completed on the Zooniverse app, available for Android and Apple devices.

### BACKYARD WORLDS: PLANET 9

Using data from NASA's Wide-field Infrared Survey Explorer (WISE), this searches the realm beyond Neptune for new brown dwarfs and planets to gain a better understanding of how both stars and planets form. The project is also on the hunt for the elusive Planet Nine, whose presence has been suggested by models and may have already been imaged with NASA's WISE telescope. Though we are yet to observe Planet Nine, eagle-eyed participants in the project are keeping their eyes peeled.

### AI4MARS


Knowing how to effectively navigate the Martian terrain is crucial for exploration missions. NASA's Spirit got stuck in a sand trap, ending its seven-year mission. Opportunity and Curiosity also experienced sand-related issues. Opportunity was able to navigate itself out of the sand, and Curiosity changed course before succumbing to a similar fate. In this Zooniverse project, you can help future Martian rovers navigate the terrain more effectively and avoid potentially dangerous situations by labelling images from Curiosity, helping to create the first open-source navigation-classification dataset of Mars.

### STAR NOTES

This novel project involves transcribing the notes of early female astronomers. The notebooks of these astronomers and Harvard Computers have been digitised, and the aim of Star Notes is to link these notebooks back to the original source material, 500,000 glass-plate photographs which represent the first-ever pictures of the visible universe.

### ZWICKY CHEMICAL FACTORY

Spectroscopy is used to understand the chemical composition of supernovae, shedding light on what type of star exploded. You can help classify these explosions by comparing spectral data against known reference data and assessing the fit. The project involves comparing your spectral line against five potential matches and choosing which (if any) are the closest match.

## STARDUST@HOME

**STARDUSTATHOME.SSL.BERKELEY.EDU**

Join fellow volunteers in the hunt for interstellar dust particles embedded in aerogel that were collected and brought back to Earth aboard NASA's Stardust spacecraft. You need a sharp eye for this project as the dust particles are only about a micron in size, and the collector plates are littered with numerous flaws, cracks and uneven surfaces.

## AURORASAURUS

**AURORASAURUS.ORG**

If you're lucky enough to live in a part of the world where aurora sightings are possible, this project is perfect for you. Aurorasaurus allows participants to log aurora sightings via the submission of a report on the website or by sending a tweet on Twitter. Along with contributing to scientific understanding of aurorae, participants earn badges.

## COSMOQUEST

**COSMOQUEST.ORG**

Projects follow a similar format to Zooniverse, with an introduction into the projects along with step-by-step instructions on how to carry out each task. There are three projects on CosmoQuest: Moon Mappers, Mars Mappers and Mercury Mappers. Though these are currently down for maintenance, they will be back up and running soon.

LEVEL 3 HIGH-INPUT AND MORE SPECIALISED

These projects require some existing knowledge, and you may need to work closely with scientists from various institutions in furthering discoveries.

# PRO-AM COLLABORATIONS

When scientists require the help of citizens with more specialist knowledge, they can reach out and partner with amateur astronomers in what is known as a PRO-AM collaboration. While a lot of professional organisations reach out to astronomy groups directly, there are many that advertise opportunities online and welcome amateur astronomers from around the world to participate.

## HOYS CITIZEN SCIENCE

**HOYS.SPACE**

If you are an avid astrophotographer, this may be the project for you. The Hunting Outbursting Young Stars (HOYS) project works with amateur astronomers around the world to hunt and study outbursting young stars, which involves long-term photometric monitoring of young stellar clusters. The project requires images of target objects, most of which are also interesting to photograph - you may even have already captured them. Contributors then upload their images onto the HOYS system and follow further processing steps. There are detailed steps on how to get involved presented on the HOYS website, along with an informative step-by-step video.

## AMERICAN ASSOCIATION OF VARIABLE STAR OBSERVERS (AAVSA)

**AAVSO.ORG/GET-INVOLVED**

This project involves both variable star observations and data mining for those without telescopes. From an observational perspective the project requires contributors to observe and record variable stars from a list of target stars following an in-depth tutorial presented by AAVSA. For those who would rather contribute from the comfort of their own home, there are numerous data-mining projects to get involved with, each with their own aims and objectives.

# IMAGE-PROCESSING SITES

## JUNOCAM

**MISSIONJUNO.SWRI.EDU**

Create your very own stunning images of Jupiter by downloading and processing raw images captured by the Juno spacecraft. Here users are encouraged to process images in their own way, from simple cropping and colour enhancements to creating collages and adding advanced colour reconstruction. There is also an online gallery for you to view other users' contributions and upload your own images.

## CHANDRA

**CHANDRA.HARVARD.EDU/PHOTO/OPENFITS**

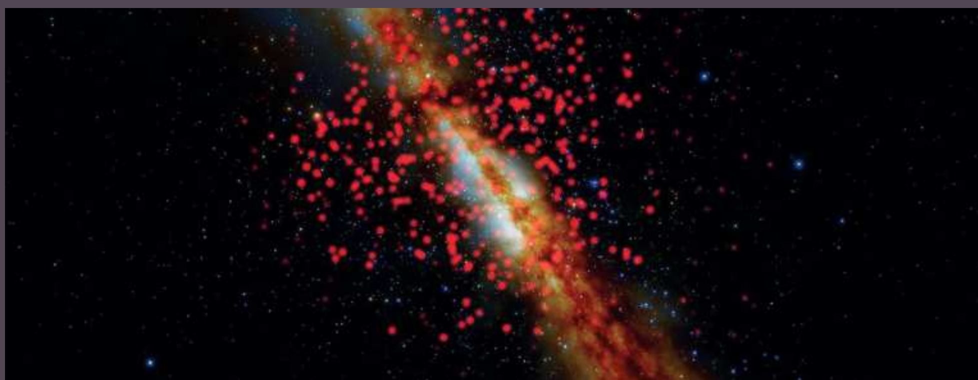
For those of you looking for a little more of a challenge with your image-processing antics, the Chandra X-Ray Observatory may be for you. Here you can create your own images from FITS (Flexible Image Transport System) files of some of the most iconic Chandra images. There are various tutorials to guide you through the image processing, as well as related blog articles.

## HUBBLE

**HUBBLE.STSCI.EDU/GET _ INVOLVED**

Fancy embarking on a new image-processing adventure? There are many beautiful images waiting to be discovered within datasets that are available to the public in the Hubble archive. Although there are tutorials available, this project is more suited to those with good knowledge of image-processing software and Hubble instruments in order to pick out useful datasets for image reconstruction.

# CITIZEN SCIENCE IN THE NEWS



© NOIRLab/NSF/AURA/J. da Silva

**Right:** 3D map of 525 brown dwarfs in the Sun's neighbourhood, 38 of which were discovered by citizen scientists

## CITIZEN SCIENTISTS DISCOVER DOZENS OF BROWN DWARFS NEAR EARTH

Thanks to citizen scientists taking part in the Zooniverse project Backyard Worlds: Planet 9, scientists have been able to produce the most complete 3D map of brown dwarfs neighbouring our Solar System, within 65 light years of the Sun. The map contains 525 brown dwarfs, including 38 that were discovered by the Backyard Worlds: Planet 9 citizen science project.

Brown dwarfs are an oddity. Neither planet nor star, they're tricky to study as they're incredibly faint and relatively small. In addition to the impressive 3D map created, scientists also discovered that cool brown dwarfs are more rare in the Sun's immediate neighbourhood – approximately seven light years – than astronomers previously thought. It is therefore possible that these particular objects are simply too faint to find using existing telescopes. Backyard Worlds: Planet 9 has already proven to be a huge help to scientists studying brown dwarfs, but with the project only 29 per cent complete at the time of writing, there is still plenty of room for more surprises and scientific discoveries. You never know, one lucky citizen scientist may be the first to spot Planet Nine.

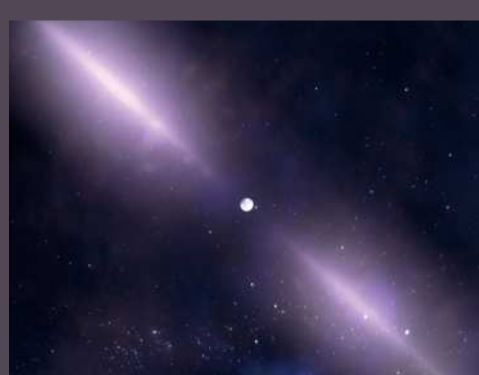
## EINSTEIN@HOME UNVEILS IDENTITY OF MYSTERIOUS GAMMA-RAY SOURCE

Using data supplied by NASA's Fermi Gamma-ray Space Telescope and the computational power of all those participating in the Einstein@Home project, scientists have revealed a rapidly spinning neutron star is located at the core of a celestial object known as PSR J2039-5617.

The exotic gamma-ray pulsar rotates about 377 times each second and orbits with a star about a sixth the mass of our Sun. This celestial dance is heading for a destructive finale, as the pulsar is slowly evaporating its stellar companion.

These so-called 'spider' binary pulsar systems are given arachnid names such as 'black widows' or 'redbacks' after species of spider where the females are known to kill the males after mating.

For many years a pulsar had been inferred to exist at the heart of PSR J2039–5617, but it was only after the contributions from Einstein@Home participants that a formal identification was possible. The project combed through ten years of archival observations from NASA's Fermi Gamma-ray Space Telescope. Analysing this much data would have taken 500 years on a single computer, but by making use of the Einstein@Home program, analysis was achieved in just two months. This discovery is a prime example of how crucial citizen science is, proving that you can be a valuable piece of the puzzle without really lifting a finger.



© NASA

**Left:** An artist's impression of a pulsar

**Right:** STEVE differs in colour from normal aurorae

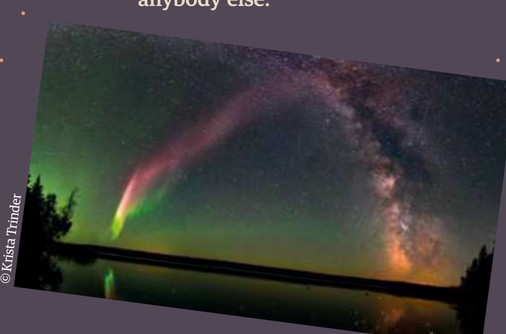
## CITIZEN SCIENTISTS' DISCOVERY OF STEVE

Strong Thermal Emission Velocity Enhancement, or STEVE, has been making headlines since the discovery of the aurora-like phenomenon. Though formal research on the discovery was published in 2018, avid photographers and citizen scientists have been photographing STEVE since 2015, reporting 30 instances of the purple-and-green picket fence in the sky.

Though observations had been going on for years, STEVE remained obscure until the citizen science project Aurorasaurus collaborated with citizen scientists and various other researchers to publish the first scientific paper describing the phenomenon.

Citizen scientists are pivotal in STEVE research. Their time-lapse images are usually carried out for longer than scientific observations, therefore building a more in-depth picture of the optical phenomenon. Their contributions don't go unnoticed, with many citizen scientists' names appearing alongside other researchers on published papers.

Scientists currently know very little about STEVE, and while data can suggest if an aurora will be visible, indicators for STEVE have yet to be identified. However, avid aurora chasers always have their cameras at the ready and have a knack for spotting and documenting STEVE before anybody else.



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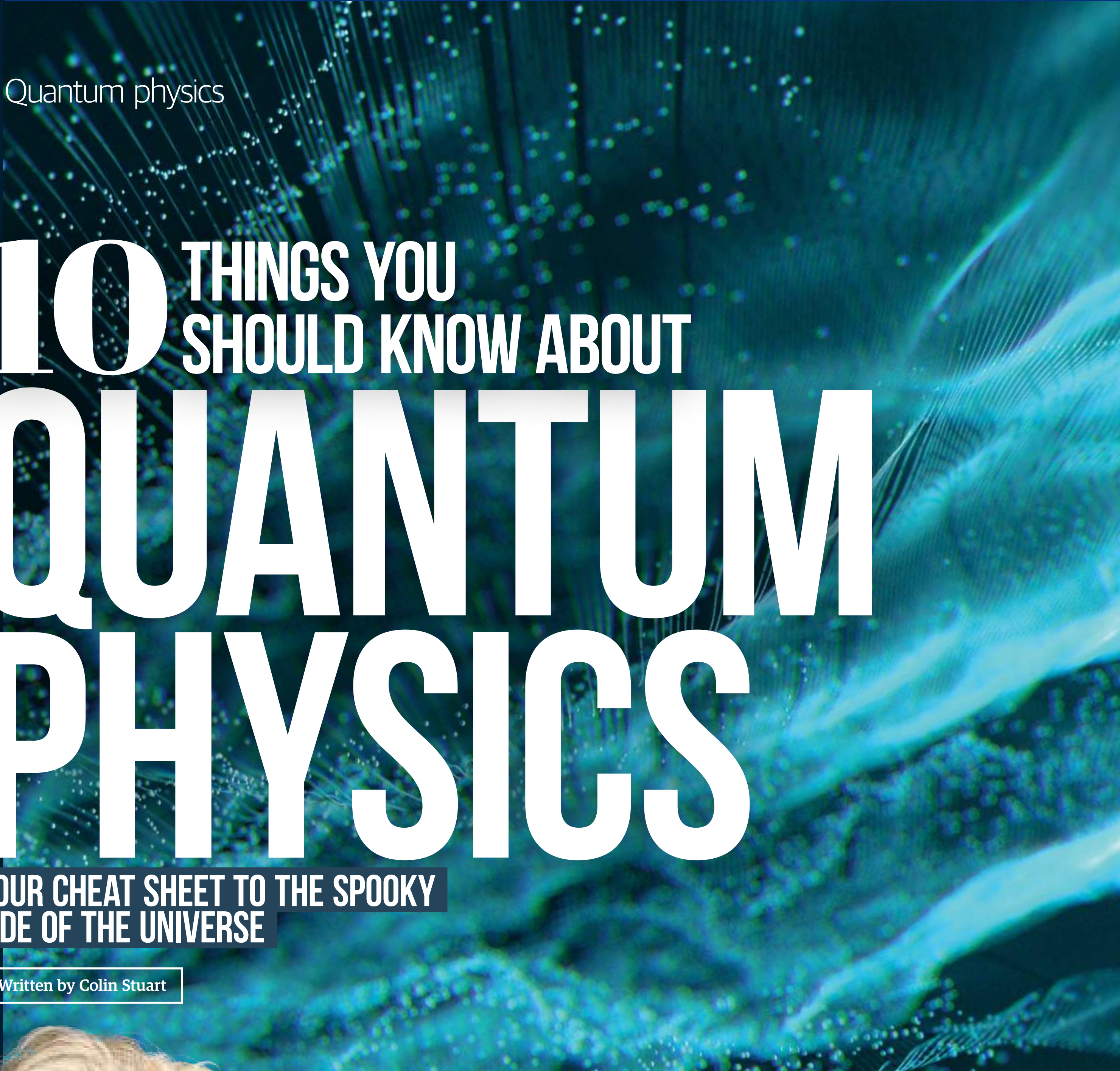

# 10 THINGS YOU SHOULD KNOW ABOUT QUANTUM PHYSICS

## YOUR CHEAT SHEET TO THE SPOOKY SIDE OF THE UNIVERSE

Written by Colin Stuart

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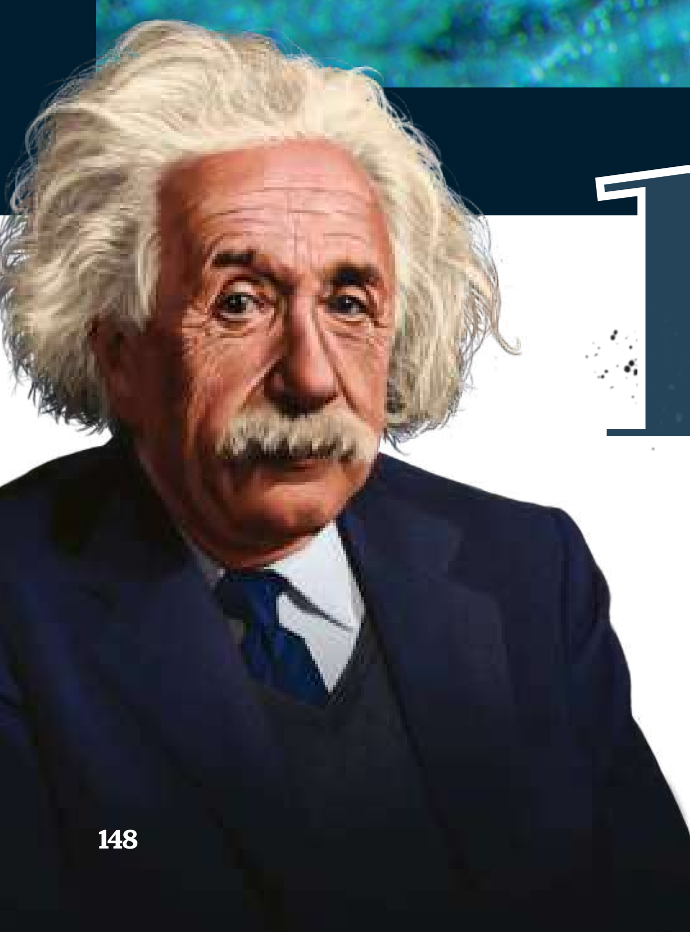


## 1 THE QUANTUM WORLD IS LUMPY

The quantum world has a lot in common with shoes. You can't just go to a shop and pick out trainers that are an exact match for your feet. Instead you're forced to choose between pairs that come in predetermined sizes.

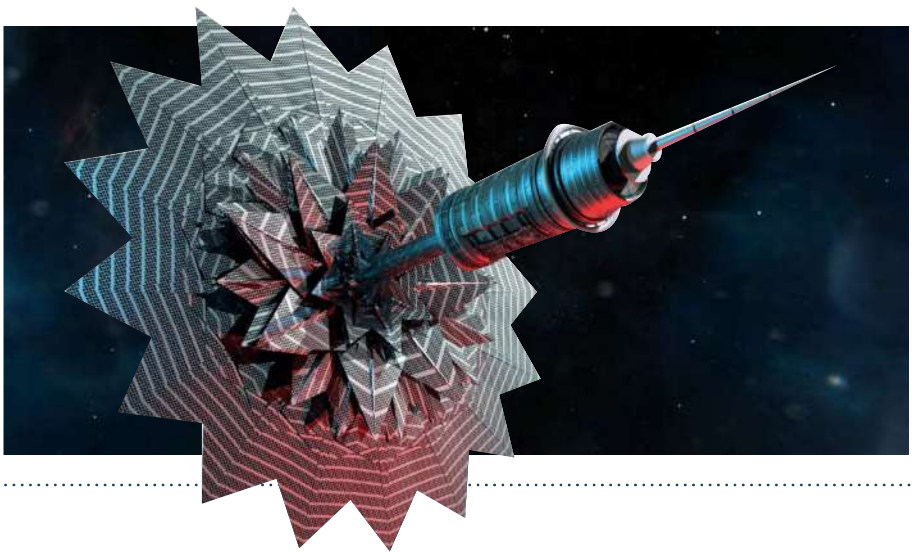
The subatomic world is similar. Albert Einstein won a Nobel Prize for proving that energy is quantised. Just as you can only buy shoes in multiples of half a size, so energy only comes in multiples of the same 'quanta' – hence the name quantum physics.

The quanta here is the Planck constant, named after Max Planck, the godfather of quantum physics. He was trying to solve a problem with our understanding of hot objects like the Sun. Our best theories couldn't match the observations of the energy they kick out. By proposing that energy is quantised, he was able to bring theory neatly into line with experiment.

# 2 SOMETHING CAN BE BOTH WAVE AND PARTICLE

J. J. Thomson won the Nobel Prize in 1906 for his discovery that electrons are particles. Yet his son George won the Nobel Prize in 1937 for showing that electrons are waves. Who was right? The answer is both of them. This so-called wave-particle duality is a cornerstone of quantum physics. It applies to light as well as electrons. Sometimes it pays to think about light as an electromagnetic wave, but at other times it's more useful to picture it in the form of particles called photons.

A telescope can focus light waves from distant stars, and also acts as a giant light bucket for collecting photons. It also means that light can exert pressure as photons slam into an object. This is something we already use to propel spacecraft with solar sails, and it may be possible to exploit it in order to manoeuvre a dangerous asteroid off a collision course with Earth.



© Getty; Tobias Roetsch

**Left:** As particles, light can be used to propel spacecraft through the cosmos at high speeds

# 3 OBJECTS CAN BE IN TWO PLACES AT ONCE

Wave-particle duality is an example of superposition. That is, a quantum object existing in multiple states at once. An electron, for example, is both 'here' and 'there' simultaneously. It's only once we do an experiment to find out where it is that it settles down into one or the other.

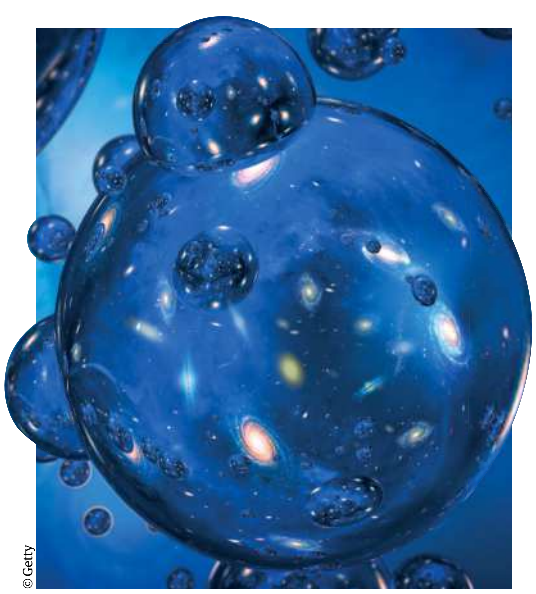
This makes quantum physics all about probabilities. We can only say which state an object is most likely to be in once we look. These odds are encapsulated into a mathematical entity called the wave function. Making an observation is said to 'collapse' the wave function, destroying the superposition and forcing the object into just one of its many possible states.

This idea is behind the famous Schrödinger's cat thought experiment. A cat in a sealed box has its fate linked to a quantum device. As the device exists in both states until a measurement is made, the cat is simultaneously alive and dead until we look.

© Getty

**Right:** Erwin Schrödinger used the idea of a cat in a box to simplify superposition

# 4 IT MAY LEAD US TOWARDS A MULTIVERSE



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**Left:** We could just be one bubble of many, each containing a different version of a universe

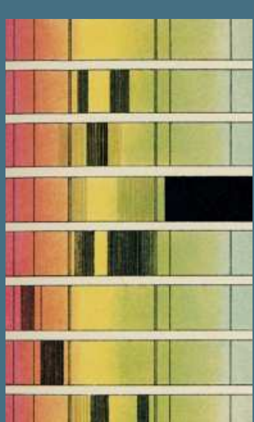
The idea that observation collapses the wave function and forces a quantum 'choice' is known as the Copenhagen interpretation of quantum physics. However, it's not the only option on the table. Advocates of the 'many worlds' interpretation argue that there is no choice involved at all. Instead, at the moment the measurement is made, reality fractures into two copies of itself: one in which we experience outcome A, and another where we see outcome B unfold. It gets around the thorny issue of needing an observer to make stuff happen - does a dog count as an observer, or a robot?

Instead, as far as a quantum particle is concerned, there's just one very weird reality consisting of many tangled-up layers. As we zoom out towards the larger scales that we experience day to day, those layers untangle into the worlds of the many worlds theory. Physicists call this process decoherence.

## 5 IT HELPS US CHARACTERISE STARS

Danish physicist Niels Bohr showed us that the orbits of electrons inside atoms are also quantised. They come in predetermined sizes called energy levels. When an electron drops from a higher energy level to a lower energy level, it spits out a photon with an energy equal to the size of the gap. Equally, an electron can absorb a particle of light and use its energy to leap up to a higher energy level.

Astronomers use this effect all the time. We know what stars are made of because when we break up their light into a rainbow-like spectrum, we see colours that are missing. Different chemical elements have different energy level spacings, so we can work out the constituents of the Sun and other stars from the precise colours that are absent.



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**Left:** The spectra of stars can tell us what elements they contain, giving clues to their age and other characteristics

© Getty

**Right:** Quantum tunnelling is the finite possibility that a particle can break through an energy barrier

## 6 WITHOUT IT THE SUN WOULDN'T SHINE

The Sun makes its energy through a process called nuclear fusion. It involves two protons - the positively charged particles in an atom - sticking together. However, their identical charges make them repel each other, just like two north poles of a magnet. Physicists call this the Coulomb barrier, and it's like a wall between the two protons.

Think of protons as particles and they just collide with the wall and move apart: no fusion, no sunlight. Yet think of them as waves and it's a different story. When the wave's crest reaches the wall, the leading edge has already made it through. The wave's height represents where the proton is most likely to be. So although it is unlikely to be where the leading edge is, it is there sometimes. It's as if the proton has burrowed through the barrier, and fusion occurs. Physicists call this effect 'quantum tunnelling'.

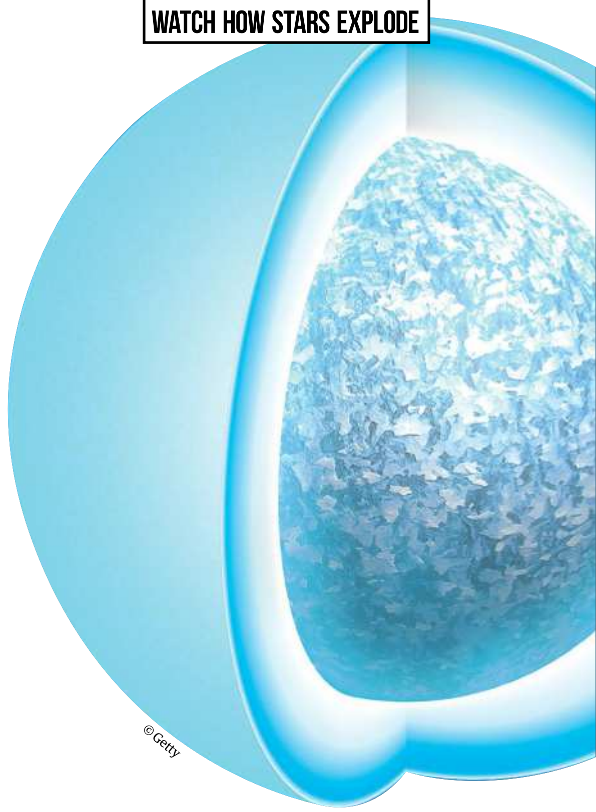
**"THEIR IDENTICAL CHARGES MAKE THEM REPEL EACH OTHER, JUST LIKE TWO NORTH POLES OF A MAGNET"**

## 7 IT STOPS DEAD STARS COLLAPSING

Eventually fusion in the Sun will stop and our star will die. Gravity will win and the Sun will collapse, but not indefinitely. The smaller it gets, the more material is crammed together. Eventually a rule of quantum physics called the Pauli exclusion principle comes into play. This says that it is forbidden for certain kinds of particles - such as electrons - to exist in the same quantum state. As gravity tries to do just that, it encounters a resistance that astronomers call degeneracy pressure. The collapse stops, and a new Earth-sized object called a white dwarf forms.

Degeneracy pressure can only put up so much resistance, however. If a white dwarf grows and approaches a mass equal to 1.4 Suns, it triggers a wave of fusion that blasts it to bits. Astronomers call this explosion a Type Ia supernova, and it's bright enough to outshine an entire galaxy.

AR SCAN HERE
WATCH HOW STARS EXPLODE



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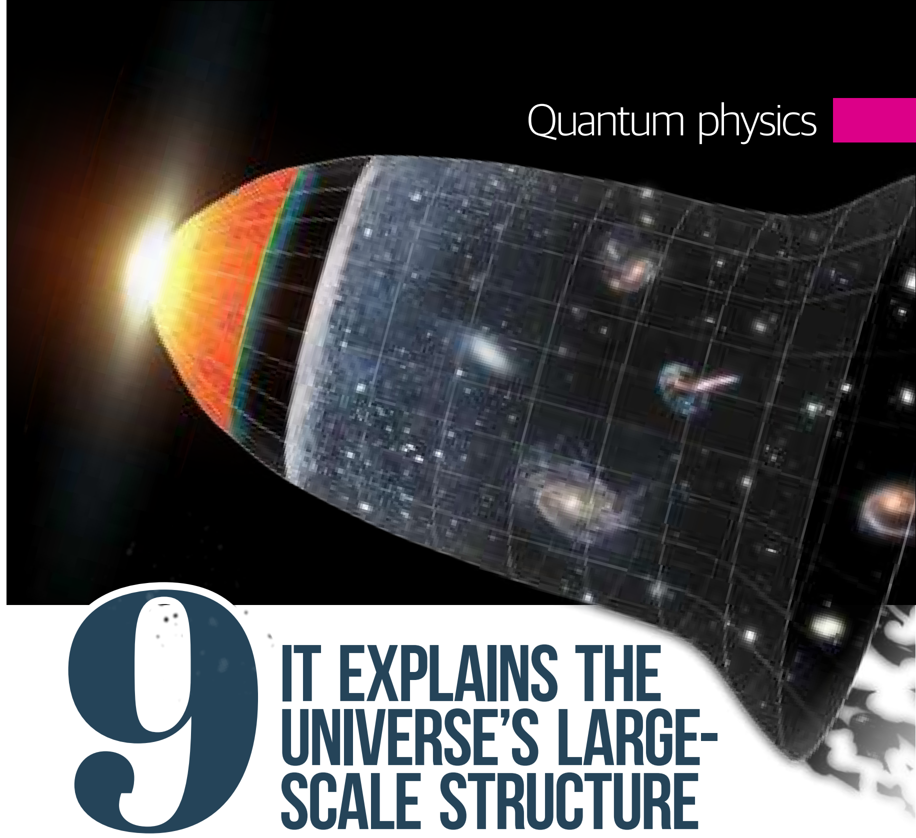
**Right:** It's theorised that white dwarfs' cores may crystallise as they age



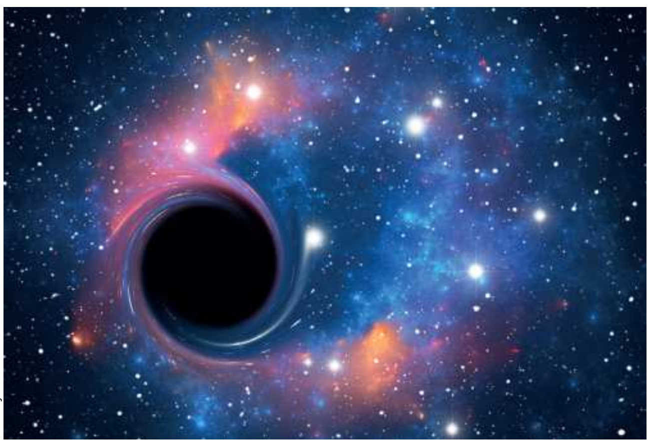
© Tobias Roetsch

## 8 IT CAUSES BLACK HOLES TO EVAPORATE

A quantum rule called the Heisenberg uncertainty principle says that it's impossible to perfectly know two properties of a system simultaneously. The more accurately you know one, the less precisely you know the other. This applies to momentum and position, and separately to energy and time.

It's a bit like taking out a loan. You can borrow a lot of money for a short amount of time, or a little cash for longer. This leads us to virtual particles. If enough energy is 'borrowed' from nature then a pair of particles can fleetingly pop into existence before rapidly disappearing so as not to default on the loan.

Stephen Hawking imagined this process occurring at the boundary of a black hole, where one particle escapes (as Hawking radiation) but the other is swallowed. Over time the black hole slowly evaporates, as it's not paying back the full amount it has borrowed.



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**Above:** Starting out as a singularity, the universe has been expanding for 13.8 billion years

**Left:** Not everything that falls into a black hole disappears - some matter escapes

## 9 IT EXPLAINS THE UNIVERSE'S LARGE-SCALE STRUCTURE

Our best theory of the universe's origin is the Big Bang. Yet it was modified in the 1980s to include another theory called inflation. In the first trillionth of a trillionth of a trillionth of a second, the cosmos ballooned from smaller than an atom to about the size of a grapefruit. That's a whopping $10^{78}$ times bigger. Inflating a red blood cell by the same amount would make it larger than the entire observable universe today.

As it was initially smaller than an atom, the infant universe would have been dominated by quantum fluctuations linked to the Heisenberg uncertainty principle. Inflation caused the universe to grow rapidly before these fluctuations had a chance to fade away. This concentrated energy into some areas rather than others - something astronomers believe acted as seeds around which material could gather to form the clusters of galaxies we observe now.

## 10 IT IS MORE THAN A LITTLE 'SPOOKY'

As well as helping to prove that light is quantum, Einstein argued in favour of another effect that he dubbed 'spooky action at distance'. Today we know that this 'quantum entanglement' is real, but we still don't fully understand what's going on. Let's say that we bring two particles together in such a way that their quantum states are inexorably bound, or entangled. One is in state A, and the other in state B.

The Pauli exclusion principle says that they can't both be in the same state. If we change one, the other instantly changes to compensate. This happens even if we separate the two particles from each other on opposite sides of the universe. It's as if information about the change we've made has travelled between them faster than the speed of light, something Einstein said was impossible.

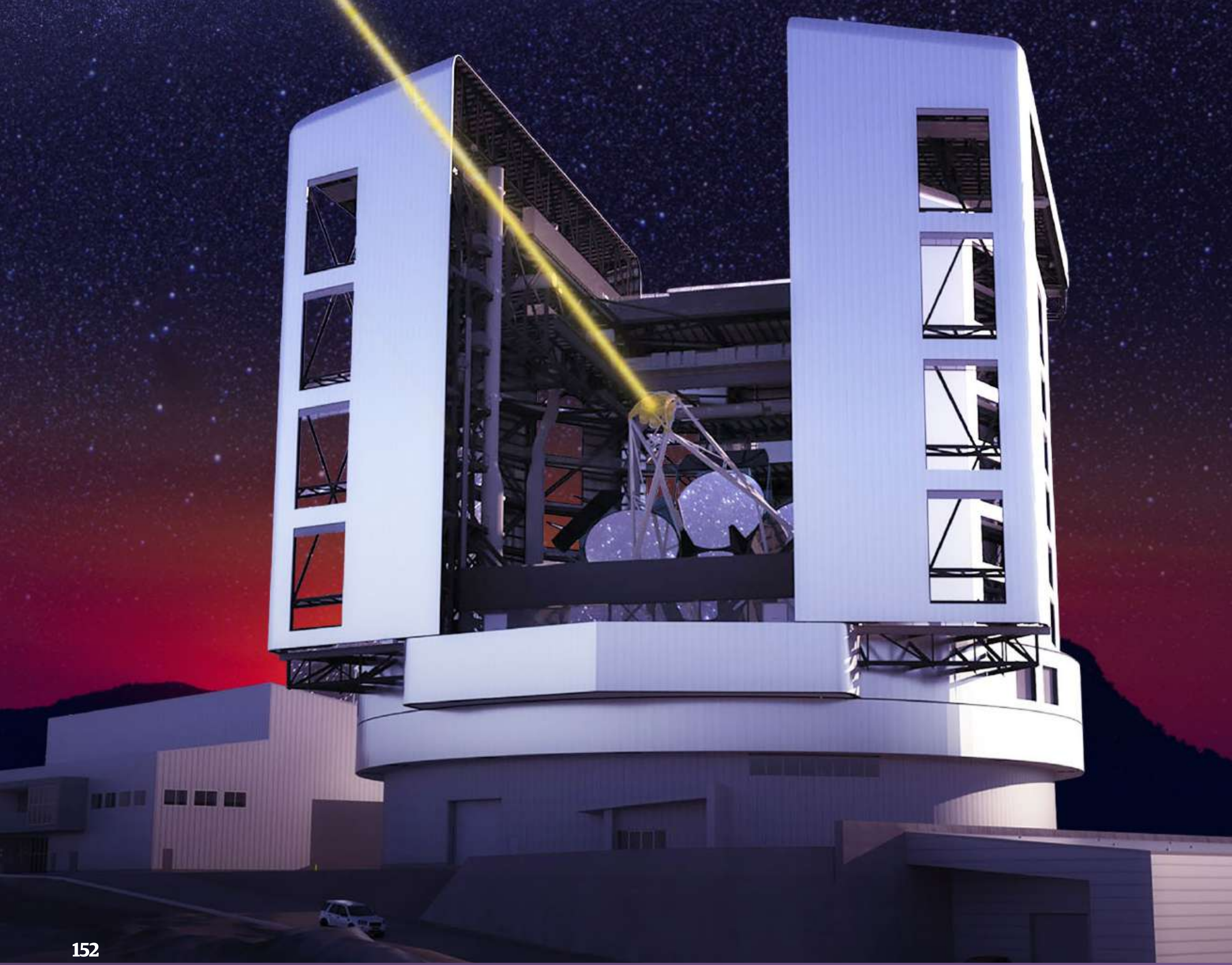
© Getty

**Right:** The properties of a particle can be 'teleported' through quantum entanglement

# NEW SEARCH FOR ALIEN LIFE

## ASTRONOMERS HAVE LONG ASKED WHETHER OR NOT WE ARE ALONE, AND NOW WE'VE ENTERED AN EXCITING NEW ERA

Reported by Mike Wall and David Crookes



For thousands of years humans have speculated that the cosmos is teeming with planets, many of which could support life. Our questioning has tapped into a long-held desire to know our place in the universe – a core human yearning which has preoccupied some of history's greatest minds. But speculation is about as far as humans got until we invented telescopes and developed a proper understanding of the scientific method a few centuries ago. Now scientists are making considerable progress in the search for alien life, and the past decade has proven pivotal. Some big discoveries may be coming soon, but where has the hunt for life taken us, and where is it heading?

One of the first modern searches for life took place in August 1924, when astronomer David Peck Todd and an inventor called Charles Jenkins wanted to listen for messages from Mars. They asked the US Army and Navy to turn off their stations so they could use their radio-photo message machine to carry out a search. Alas, they drew a blank. In 1960, however, the search for extraterrestrial intelligence (SETI) intensified when Cornell University astronomer Frank Drake used a radio telescope in West Virginia to listen for interstellar radio waves coming from the stars Tau Ceti and Epsilon Eridani. Called Project Ozma, this effort incorporated ideas from a seminal 1959 paper by Giuseppe Cocconi and Philip Morrison. But again it detected no recognisable signals.

Undeterred, scientists have been scanning the heavens for technosignatures ever since. Initially they focused almost exclusively on radio signals, but flashes of light are now being sought too. These are the targets of increasingly common 'optical SETI' efforts. But then SETI scientists have to keep an open mind. After all, we don't know what sorts of messages advanced alien civilisations might beam out. It means astronomers in the field are generally looking for signals that appear weird and artificial. They search for something coming from deep space that isn't produced by any known natural astrophysical phenomenon.

An identified signal would ideally recur so it can be studied repeatedly and in detail. One-offs can remain forever mysterious, as 1977's famous Wow! signal shows. In that case, a radio dish operated by Ohio State University picked up something so intriguing that astronomer Jerry Ehman wrote 'Wow!' on the data printout. Researchers scoured that same patch of sky again and again, hoping to get another ping, but they never did.

What's perhaps more frustrating is that SETI has historically been a shoestring operation, and finding enough money to keep the telescopes running has been a consistent problem. US Congress axed a planned NASA-SETI project in 1993, with Senator Richard Bryan saying: "This hopefully will be the end of Martian hunting season at the taxpayer's expense."

ET hunters have mostly had to turn to the private sector for cash, and without steady funding, progress became slow for several years. Things changed recently when private money began to flow more freely into SETI research. Most of it comes from one man – tech billionaire Yuri Milner – but his passion for the search for alien life prompted him to establish an ambitious program called Breakthrough Initiatives in 2015.

Projects under the Breakthrough umbrella include the $100 million (£73 million) Breakthrough Listen SETI campaign and the $100 million (£73 million) Breakthrough Starshot, which aims to develop the technology required to send tiny robotic probes to nearby exoplanet systems at about 20 per cent the speed of light. There's also Breakthrough Message, which aims to help humanity craft the best possible message to send out into the cosmos and encourages debate and conversation about SETI in general.

Even so, there is considerable debate within the scientific community about SETI. Some people, including the late physicist Stephen Hawking, have argued that it's unwise to advertise our presence to aliens, whose nature and intent are complete mysteries to us. "We should be wary of answering back," he said. "Meeting an advanced civilisation could be like Native Americans encountering Columbus. That didn't turn out so well."

Other researchers think that any creatures advanced enough to travel to Earth to enslave or eat us would already know we're here. Just to be on the safe side, Breakthrough Message pledges not to actually broadcast any SETI signals until this


**Right: Hollywood has long tapped into our fascination with alien life, as 1982's *E.T. the Extra-Terrestrial* shows**

© Getty

© GMTO Corporation/M3 Engineering; Getty

debate has played itself out – though humanity has already beamed out messages on multiple occasions, most famously in 1974 with the Arecibo message. Humanity is also leaking radio signals in all directions at all times, providing cosmic bread crumbs for anyone close enough to find them. Around the same time that SETI was getting off the ground, planetary scientists began getting their first good look at alien worlds.

In 1965, Mariner 4 flew by Mars, returning the first close-up images of the Red Planet. Those photos revealed a dry, heavily cratered and seemingly desolate world, forcing many scientists to recalibrate previously optimistic notions of Mars' habitability. Hopes of a life-supporting Mars had been famously stoked around the turn of the 19th century by astronomer Percival Lowell, who claimed that channels on the planet were actually canals built by intelligent creatures.

But the optimists got some good news in 1971 after Mariner 9 arrived in orbit around Mars, becoming the first spacecraft to circle another planet. This intrepid probe spotted river channels and other evidence of past liquid-water activity on the Martian surface. These discoveries helped spur NASA to develop two ambitious life-hunting Mars missions, Viking 1 and 2, which launched a few weeks apart in 1975.

The twin Viking landers each carried four biology experiments which hunted for signs of microbial life in the red dirt. One of those, called the Labeled Release (LR) experiment, returned data consistent with evidence of microbial life. Indeed, LR principal investigator Gil Levin argued that the Vikings found evidence of Mars life. However, most scientists who studied the data disagreed with Levin, determining that the data could be explained by abiotic chemical reactions.

The Viking results taught NASA some valuable lessons – chiefly that we didn't know enough about Mars to mount a proper life hunt there. The space agency eventually embarked on a long-term 'follow the water' exploration strategy, seeking to learn more about ancient environmental conditions on the Red Planet and how they changed over time.

This strategy gave us many prominent Mars missions over the past few decades, including Mars Odyssey, the Mars Reconnaissance Orbiter, Mars Atmosphere and Volatile Evolution (MAVEN), the rovers Spirit, Opportunity, Curiosity and Perseverance and the Phoenix lander. These robotic explorers did their jobs well, finding lots of evidence that ancient Mars was quite wet, and helping scientists better understand why, how and when the Red Planet transitioned to the frigid desert world it is today. Curiosity has taken this work the furthest, finding that its landing site, the 154-kilometre (96-mile) Gale crater, hosted a long-lived lake-and-stream system billions of years ago that could have supported Earth-like life.

Meanwhile, other scientists have continued the hunt for Mars life, focusing on aliens that may have fallen fortuitously to Earth. Billions of Red Planet rocks have made their way here from Mars after being blasted into space by powerful asteroid or comet impacts. A lot of Earth material has ended up on Mars as well, but the ledger is decidedly unbalanced – the Sun's powerful gravity pulls more stuff inward, towards Earth. This extensive rock-swapping has led some scientists to postulate that life actually arose first on Mars, then made its way to Earth later.

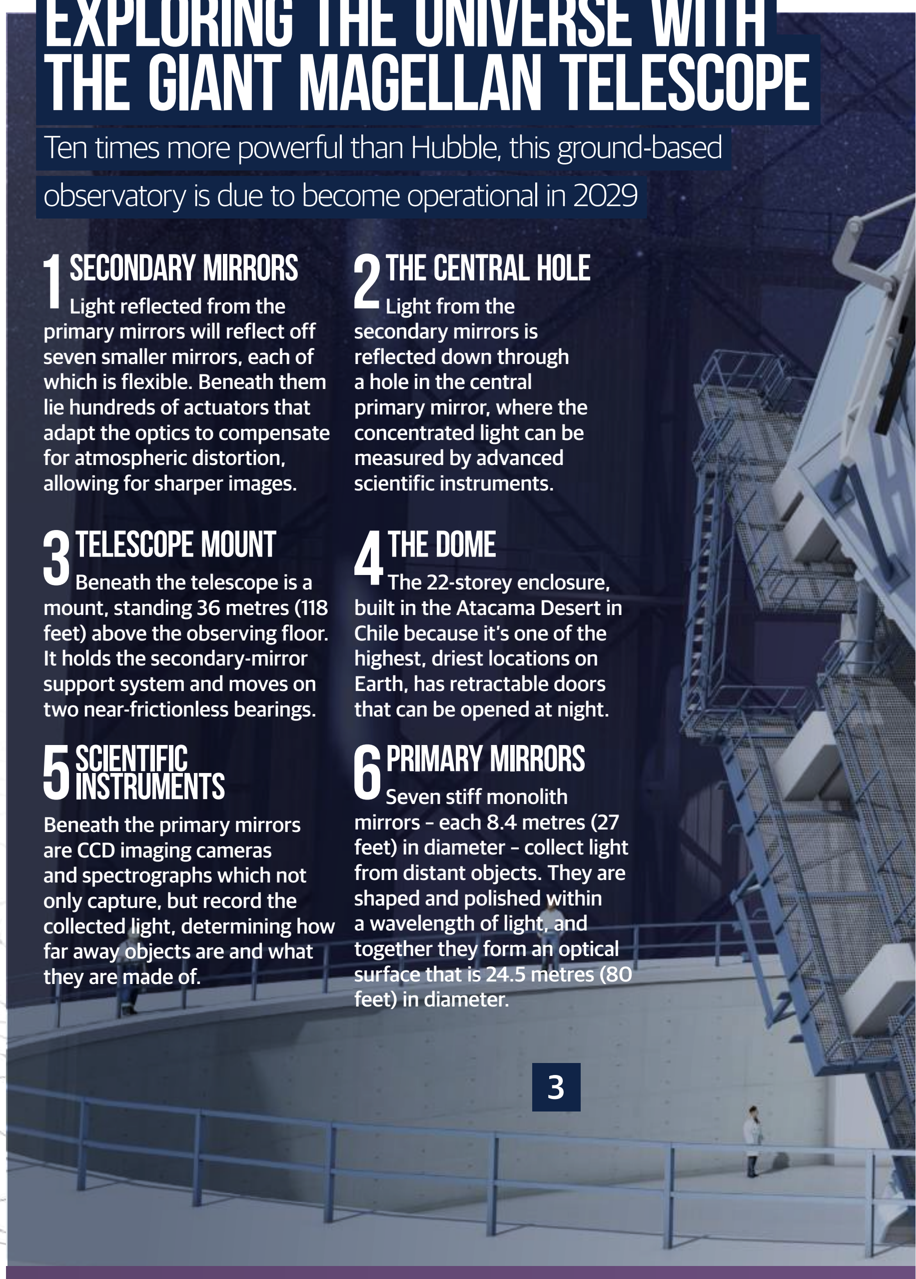
In 1996 researchers announced they'd found potential signs of life in one such Mars meteorite, known as Allan Hills 84001 (ALH84001). It was a very big deal. The result was published in the prestigious journal *Science*, and President Bill Clinton held a press conference about the news on the White House lawn. But the ALH84001

**Below:** This stained-glass window depicts the Arecibo transmission, an interstellar radio message broadcast into space in 1974 by Frank Drake




# EXPLORING THE UNIVERSE WITH THE GIANT MAGELLAN TELESCOPE

Ten times more powerful than Hubble, this ground-based observatory is due to become operational in 2029




### 1 SECONDARY MIRRORS

Light reflected from the primary mirrors will reflect off seven smaller mirrors, each of which is flexible. Beneath them lie hundreds of actuators that adapt the optics to compensate for atmospheric distortion, allowing for sharper images.

### 2 THE CENTRAL HOLE

Light from the secondary mirrors is reflected down through a hole in the central primary mirror, where the concentrated light can be measured by advanced scientific instruments.

### 3 TELESCOPE MOUNT

Beneath the telescope is a mount, standing 36 metres (118 feet) above the observing floor. It holds the secondary-mirror support system and moves on two near-frictionless bearings.

### 4 THE DOME

The 22-storey enclosure, built in the Atacama Desert in Chile because it's one of the highest, driest locations on Earth, has retractable doors that can be opened at night.

### 5 SCIENTIFIC INSTRUMENTS

Beneath the primary mirrors are CCD imaging cameras and spectrographs which not only capture, but record the collected light, determining how far away objects are and what they are made of.

### 6 PRIMARY MIRRORS

Seven stiff monolith mirrors – each 8.4 metres (27 feet) in diameter – collect light from distant objects. They are shaped and polished within a wavelength of light, and together they form an optical surface that is 24.5 metres (80 feet) in diameter.

story ended up going down a Viking path. Other scientists picked at the claim, and a consensus emerged that the meteorite evidence was ambiguous at best. But like Levin, the team held firm in its findings, and continues to do so today.

NASA and the broader exploration community weren't focused solely on Mars for all these years, however. The Cassini-Huygens mission, which ended in September 2017, transformed scientists' understanding of the Saturn system and our Solar System's potential to host alien life. That mission found that Titan, Saturn's largest moon, has a hydrocarbon-based weather system and that the frigid moon's surface harbours lakes and seas of liquid ethane and methane. Life could swim around in these seas, though it would have to be very different from the life we know here on Earth.

Cassini also spotted geysers blasting from the south pole of another Saturn moon, the ice-covered

**Right:** Viking 1 was sent to Mars in 1975, becoming the first lander to trundle along the surface of the Red Planet

© NASA


"MEETING AN ADVANCED CIVILISATION COULD BE LIKE NATIVE AMERICANS ENCOUNTERING COLUMBUS"

STEPHEN HAWKING

© Adrian Mann

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**Left:** If life does exist on other planets, it may not be anything more advanced than microorganisms

© Getty

**Below:** Russian-Israeli entrepreneur Yuri Milner launched Breakthrough Initiatives in July 2015 to investigate the possibility of life in the universe

Enceladus. This discovery, among other Cassini observations, revealed that Enceladus harbours a big ocean of salty liquid water beneath its shell.

These geysers blast up huge plumes of water ice and other material in clouds so substantial that they create Saturn's E ring. Cassini flew through one such plume on multiple occasions, gathering samples that scientists analysed for clues about the moon's subsurface environment.

The researchers found carbon-containing organic compounds and free hydrogen, the latter of which suggests the existence of a hydrothermal system in Enceladus' buried ocean. Undersea hydrothermal vents are one popularly invoked environment for the origin of life on Earth. But Cassini didn't look for signs of life in plume material; the spacecraft wasn't equipped to do so because nobody knew about the plumes before the mission launched. Now scientists have come to realise that buried oceans are relatively common in the outer Solar System. "There are more oceans in the universe than previously thought, making the existence of extraterrestrial life more plausible," says Shunichi Kamata of Hokkaido University in Japan.

Multiple ice-covered Jupiter moons seem to have these oceans: Ganymede, Callisto and, most intriguingly, Europa. Europa's huge subsurface sea seems to be in contact with the moon's rocky core, like the ocean of Enceladus is, making possible a range of complex chemical reactions that could theoretically have led to life. Scientists think the oceans of Ganymede and Callisto are more boring, sandwiched between layers of ice. Titan seems to have a buried ocean of salty water as well, meaning the moon likely has two very different potentially habitable environments. Observations by NASA's New Horizons spacecraft indicate that liquid water may slosh beneath Pluto's surface, too.

And the list goes on. The abundance of water worlds in the outer Solar System suggests that looking for 'Earth 2.0' may not be the best life-hunting strategy after all – most of the habitable real estate in the cosmos may be buried under ice. And these revelations about our celestial backyard have come in parallel with big news about the cosmos at large.

## GOING EQUIPPED IN THE HUNT FOR ET

Telescopes and spacecraft are helping astronomers look for vital signs of life across the universe

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### KEPLER SPACE TELESCOPE

**2009 to 2018**

Searching for over nine years, Kepler enabled scientists to observe 530,506 stars and 2,662 planets from outside our Solar System. It showed that between 20 and 50 per cent of stars have planets similar in size to Earth within their habitable zone – that's a lot of potential for life.

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### FIVE-HUNDRED-METER APERTURE SPHERICAL TELESCOPE

**2016 to present**

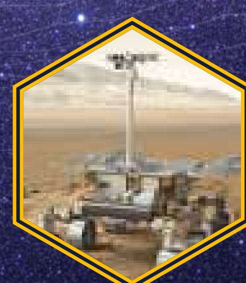
FAST uses radio waves to locate exoplanets, seeking to detect electromagnetic transmissions of artificial origin. If aliens are trying to contact us, this telescope could pick up the call!

© Tobias Roetsch

### TESS EXOPLANET-HUNTING MISSION

**2018 to present**

The Transiting Exoplanet Survey Satellite has discovered thousands of exoplanets orbiting dwarf stars. It has enabled astronomers to build a vast database of worlds that are close enough to be studied for signs of extraterrestrial life.



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### MARS 2020

**2020 to present**

Part of NASA's Mars Exploration Program, Mars 2020 is the mission which has placed the Perseverance rover on the surface of Mars. It has also launched a rotary helicopter called Ingenuity. Their primary aim is to seek signs of ancient life.

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### JAMES WEBB SPACE TELESCOPE

**2021 to 2031**

The successor to Hubble will peer back 13.5 billion years to the time when the first stars and galaxies were formed. Able to detect infrared, it will be able to determine the atmospheres of planets and detect if they are being modified by alien life.

Over the past decade or so, we've learned that our Milky Way galaxy is teeming with potentially life-supporting worlds. Much of this knowledge comes courtesy of NASA's pioneering Kepler space telescope, which operated from 2009 through to November 2018. Kepler is responsible for nearly two-thirds of the 4,400 confirmed exoplanet discoveries to date, and mission data reveals that planets outnumber stars in our galaxy. Many of those planets might bear more than a passing resemblance to Earth. Kepler found that at least 20 per cent of Milky Way stars probably host rocky planets in their habitable zones, the just-right range of orbital distances where liquid water can persist on a world's surface.

Some of these potentially habitable worlds are just a stone's throw away in the cosmic scheme of things. For example, the nearest star to the Sun – Proxima Centauri, which is about 4.2 light years away from us – hosts a roughly Earth-sized planet in the habitable zone. This world, called Proxima b, is a prime Breakthrough Starshot target. And the TRAPPIST-1 system, which lies 39 light years from us, boasts seven rocky worlds, three of which may be capable of supporting life as we know it. But both Proxima Centauri and TRAPPIST-1 are red dwarfs, like 70 per cent of the Milky Way's stellar population. Red dwarfs are small but very active stars, and their intense flaring may severely dampen planets' habitability.

Kepler's legacy is being carried on by other exoplanet missions, such as NASA's Transiting Exoplanet Survey Satellite (TESS), which is expected to find thousands of alien worlds circling nearby stars, and the European Space Agency's (ESA) CHEOPS (CHaracterising ExOPlanet Satellite), which aims to characterise some of these neighbouring worlds. The avalanche of exoplanet discoveries, as well as finds much closer to home, have brought astrobiology from the scientific fringe firmly into the mainstream. NASA is openly prioritising the search for alien life these days, as some current and coming missions show.

In July 2020 the space agency launched the Perseverance rover, which landed in February 2021 to hunt for signs of ancient Mars life and collect samples for eventual return to Earth. Finding evidence of long-dead microbes is expected to be a very tricky task, one ideally carried out by teams of scientists in well-equipped labs studying pristine pieces of Mars specifically selected for their life-preserving potential. The ESA planned to launch its own life-hunting Mars rover, called Rosalind Franklin, in July 2020 as well, but technical issues pushed the launch back to the next window – it's now scheduled for autumn 2022.

In 2024 NASA's Europa Clipper is scheduled to launch towards the Jupiter system. Clipper will orbit the gas giant but make dozens of flybys of Europa, characterising the moon's subsurface ocean and scouting out good touchdown sites for a future life-hunting lander, among other tasks. And in 2027 NASA plans to launch Dragonfly, a probe that will fly through Titan's thick, smoggy

**Right:** This illustration of Titan shows what looks like water on the surface. It's actually liquid hydrocarbons, and could indicate life

IS THERE LIFE ON SATURN'S MOON TITAN?
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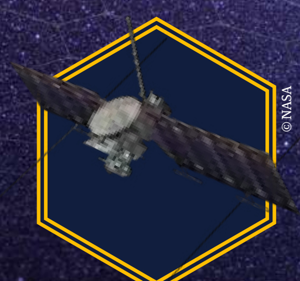

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## EUROPA CLIPPER

**2024 to 2034**

This mission plans to send an orbiter to perform as many as 50 flybys of Jupiter's icy moon Europa. By scanning close to every part of the moon, NASA hopes to use cameras, spectrometers and ice-penetrating radar to work out if Europa is capable of hosting life.

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## DRAGONFLY

**2027 to 2039**

Planning to launch in six years, a robotic rotorcraft will be sent to the surface of Saturn's largest moon Titan. After landing in 2034 it will search for the building blocks of life. It's going to take its scientific payload to multiple locations, which will give astronomers an abundance of data.

© TMT Observatory Corporation

## THIRTY METER TELESCOPE

**2027 onwards**

When it's built – high atop a volcano in Hawaii – this telescope will be one of the most powerful ever seen. Scientists are also identifying planets it could help them study for signs of life, including Proxima Centauri b.

© ESO

## EXTREMELY LARGE TELESCOPE

**2027 onwards**

Part of the European Southern Observatory, this telescope is being built in the Atacama Desert in Chile, and will be used to scan the skies for exoplanets. It will have 250 times the light-gathering area of Hubble and produce images that are 16 times sharper.

© GMTO Corporation/M3 Engineering

## GIANT MAGELLAN TELESCOPE

**2029 onwards**

This telescope will produce direct images of planets in the habitable zones of other stars. Astronomers will be able to analyse the atmospheres of those exoplanets and look for key indicators of life, potentially making some staggering breakthroughs.

# LIFE WITHIN THE SOLAR SYSTEM?

Earth is the only planet we know of that hosts life, but which other worlds could one day surprise us?

### VENUS

**Type of world:** Planet

**Minimum distance from Earth:** 225 million kilometres (139 million miles)

Venus is the hottest planet in our Solar System, so that should rule out the potential for life. But there is a theory that microbes could exist in the clouds, where temperatures are cooler. In fact, phosphine – a potential marker of life – has been observed in the clouds.

### MARS

**Type of world:** Planet

**Minimum distance from Earth:** 225 million kilometres (139 million miles)

Mars has long been seen as a prime candidate for harbouring life because of its proximity and similarity to Earth. In reality the surface of Mars is unlikely to be hospitable to life today, but microorganisms could exist in ice or water within the planet's subsurface.

### EUROPA

**Type of world:** Moon

**Minimum distance from Earth:** 780 million kilometres (485 million miles)

Cracks on the surface of Europa, one of Jupiter's moons, as well as fluctuations in its magnetic field, have led scientists to believe there is a vast ocean beneath the surface. There is a possibility that it could contain some form of life, if not in the water itself then in the upper ice layers.

### ENCELADUS

**Type of world:** Moon

**Minimum distance from Earth:** 1.272 billion kilometres (745 million miles)

Scientists believe that Saturn's sixth-largest moon has the ingredients needed for life. Aside from a global ocean beneath its icy crust, hydrogen was discovered in the plumes erupting from the south pole, meaning there's a source of chemical energy. It's our greatest hope for a discovery.

### CERES

**Type of world:** Dwarf planet

**Minimum distance from Earth:** 426 million kilometres (265 million miles)

Ceres, the largest object in the asteroid belt, has water, and it could be in liquid form, so there is a ferocious appetite to explore this celestial body further. If life is discovered it's not likely to be anything more than small microbes, but that would nonetheless represent a major breakthrough.

### TITAN

**Type of world:** Moon

**Minimum distance from Earth:** 1.6 billion kilometres (1 billion miles)

Saturn's hazy moon has a subsurface ocean of liquid water. It also has lakes and rivers of liquid methane and ethane, as well as a weather system similar to Earth's. Astronomers ponder how methane is finding its way into the atmosphere. If life exists, however, it may not be quite as we know it.

x6 Images © NASA

skies. Dragonfly's main goals involve investigating the complex chemistry that could set the stage for life's emergence and assessing Titan's habitability, but the rotorcraft will also search for biosignatures.

The agency will soon start hunting for aliens much farther afield, too. NASA's $9.7 billion (£7.1 billion) James Webb Space Telescope, the oft-delayed successor to the iconic Hubble Space Telescope, is scheduled to launch in November 2021. One of the many things the powerful new telescope will do once aloft is probe the atmospheres of nearby exoplanets for potential biosignatures – gases such as oxygen and methane, whose simultaneous presence in a world's air would provide a strong case for life.

Three highly anticipated megascopes will begin doing similar work from the ground in the next decade if all goes according to plan. The Giant Magellan Telescope (GMT) and the Extremely Large Telescope (ELT) will do their observing from the mountains of Chile, whereas the Thirty Meter Telescope (TMT) will sit atop Hawaii's Mauna Kea volcano – if the telescope team and the local community can come to an agreement.

© Getty

**Left:** What would it be like to stand on one of the seven Earth-sized planets orbiting the TRAPPIST-1 star – one of which may support life?

SETI activities may ramp up considerably soon, too, and not just because of Breakthrough Listen. The biggest radio telescope ever built, China's Five-hundred-meter Aperture Spherical Telescope (FAST), nicknamed Tianyan, came fully online in early 2020, and searching for technosignatures is one of its many charges.

This is just a partial list of the coming life-hunting activities and technologies. The full list may eventually become gloriously ungainly thanks to the continuing drop in the cost of building and launching spacecraft. This trend could eventually make astrobiology missions feasible for a variety of interested parties, from university groups to private citizens. Indeed, Milner has already mused about launching a life-hunting mission to Enceladus or Europa.

Some of this alien searching will continue to occur in Earth-based studies, and it won't just involve inspection of Mars meteorites. There's an ongoing search for a 'shadow biosphere' on our planet – an entire tree of life separate from the one that includes bacteria, bats, birds and everything else we currently recognise as alive.

This peculiar pursuit isn't so crazy if you think about it. After all, life appeared on Earth about 4 billion years ago – very quickly considering that our planet formed just 4.5 billion years ago and

remained hot and inhospitable for a long time thereafter. Life's emergence really doesn't seem that miraculous, which in turn implies that it could have happened here more than once. Given the incredible abundance of potentially habitable real estate – and that's just for Earth-like life, saying nothing of the environments that could support 'strange life' of various types – why haven't we found extraterrestrials yet?

Nobel Prize-winning physicist Enrico Fermi famously posed this question in 1950, specifically referring to intelligent aliens. Seven decades later, the answer to the so-called Fermi paradox remains elusive. 'Answers' is probably a better formulation, however, because multiple factors are most likely working together to keep us from finding intelligent aliens. Among the foremost is the vastness of space, which makes it difficult for two civilisations to touch base. Consider that Proxima b is just 4.2 light years away in a galaxy 100,000 light years wide. But 4.2 light years is an expanse that would take humanity's current spacecraft tens of thousands of years to cross.

Contact with intelligent aliens would require temporal and temperamental alignments as well: their civilisation would have to rise in sync with ours, no mean feat in a universe that's 13.8 billion years old. And ET would have to want to reach out – that's no given, either. There are many reasons why some aliens may want to keep quiet, as the pessimists have pointed out. Or maybe intelligence is rare throughout the cosmos, even if life isn't. Planet Earth has been inhabited for about 4 billion years, after all, but we've only been sending out radio waves for just a century or so and launching spacecraft since 1957. And it's very tough to find faraway microbes, which presumably have not yet invented the radio.

Our technological youth may be the biggest factor of all: we've only just begun the search for our cosmic neighbours. And that search has been halting and haphazard, conducted by small teams of dedicated researchers who have had to scrounge money to keep the lights on. But that's changing, as the exciting new missions and instruments currently in development show. We may start getting some answers very soon.


**Mike Wall**
*Space.com Senior Space Writer*
Mike joined **space.com** in 2010 as a senior writer. He has also worked as a herpetologist and wildlife biologist and holds a PhD in evolutionary biology.

**David Crookes**
*Science and technology journalist*
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.


## SEARCHING FOR LIFE ON MARS

Sarah Stewart Johnson, a planetary scientist at Georgetown University, has written a book, *The Sirens of Mars*, in which she explores science's attempts to discover life on Mars

© Brittany Waddell

**Why did you want to write this particular book about Mars?**
The book is about the search for life on Mars, but it's not just the science of it; it's about our human relationship to the planet as well. There were just so many things that were poignant and beautiful and compelling about the endeavour that will never really find expression in the pages of scientific journals. That's a large part of why I decided to write the book: this idea that Mars deserved a different type of treatment, something that captured the mystery and the wonder, and just of the entire quest.

**Why is looking for life on Mars a valuable endeavour?**
Even the discovery of simple life beyond Earth really stands to make a tremendous impact. We've had these massive advances over the last decades, but biology is still this rather descriptive science. It's because we have this one data point – we've got life on Earth, and we don't have a second data point. If we found evidence of a second genesis [a case where life arose independently of life found on Earth, rather than migrating between the two worlds], I think it'd be as revolutionary as any breakthrough that's been made in terms of thinking about ourselves and our existence.

**Do you think it's possible we'll hit the point at which scientists can confidently say there is no life on Mars?**
It's certainly possible there is no life on Mars, that we'll search and search and, like the Moon, we conclude pretty conclusively that that's it. Who knows what we'll find, but that's one of the great things about Mars. It's accessible, and we have developed so many tools and techniques where we can really do such good science on the planet. We can get there quickly and we can deploy really capable robots to do tremendously sophisticated science on the surface

**If there is no life on Mars, what happens next?**
Fortunately, there are lots of other targets – even in our own Solar System – that are really exciting to think about. All these other astrobiological destinations, like Enceladus and Europa, and Titan's a place that we're really excited about in my laboratory. A lot of our work is trying to imagine life as we don't know it and how we might detect life forms that are almost inconceivable within the confines of current thinking.

**Below:** Could our fleet of missions uncover life on the Red Planet?

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